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TEST RESULTS OF SIX-MONTH TEST OF TWO WATER ELECTROLYSIS SYSTEMS

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E.S. Mills, et al (McDonnell-Douglas
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by Biotechnology and Power Department
McDonnell Douglas Astronautics Company
Huntington Beach, California

for

MANNED SPACECRAFT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Prepared for:

National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas

Contract No. NAS9-12048

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this document may be better
studied on microfiche

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CORPORATION

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FOREWORD

The two water electrolysis systems used in the NASA space station simulation 90-day manned test (NASA CR111881) of a regenerative life support system were refurbished as required and subjected to 26-weeks of performance/endurance testing. This electrolysis systems testing was conducted by the Biotechnology and Power Department of the McDonnell Douglas Astronautics Company (MDAC), Huntington Beach, California, under contract NAS9-12048. This project was performed for the NASA Manned Spacecraft Center under the direction of R. J. Gillen of the Crew Systems Division.

The program was supervised by K. H. Houghton, M.D., Chief Advance Technology Engineer of the Biotechnology and Power Department (MDAC). E. S. Mills was the Program Manager for McDonnell Douglas. Assisting him in various aspects of the program were N. A. Jones, R. G. Livingston, P. P. Mader, N. R. Radke, J. P. Valinsky and G. W. Wells. Special technical assistance was provided by F. H. Schubert of Life Systems, Inc., under MDAC subcontract MDAC-71-4-023 in the areas of documentation reviews, acceptance testing of modules, development testing of cells and consulting in support of the testing. B. M. Greenough and R. D. Rancour of Lockheed Missiles and Space Company provided technical assistance relative to operations of the circulating electrolyte water electrolysis unit. Technical assistance was also provided by W. G. Sanderson of the Boeing Company in a support-contractor role to MSC. A summary of the results of this test program has been published by the American Society of Mechanical Engineers as engineering paper ASME-72-ENAV-5. Presentation was also made at the Environmental Control and Life Support Conference, San Francisco, California, August 14-16, 1972.

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ABSTRACT

The two water electrolysis systems used in the NASA space station simulation 90-day manned test (NASA CR-111881) of a regenerative life support system at the McDonnell Douglas Astronautics Company were refurbished as required and subjected to 26-weeks of testing. The two electrolysis units are both promising systems for oxygen and hydrogen generation and both needed extensive long-term testing to evaluate the performance of the respective cell design and provide guidance for further development. The static vapor feed unit (SVFU) uses a vapor feed and intermittent circulation of electrolyte and the circulating electrolyte unit (CEU) uses a liquid supply with continuous electrolyte circulation. Testing was conducted to evaluate performance in terms of current, pressure, variable oxygen demands, and orbital simulation. An automatic monitoring system was used to record, monitor and printout performance data at one minute, ten minute or one-hour intervals. Performance data is presented for each day of system operation for each module used during the day. Failures are analyzed, remedial action taken to eliminate problems is discussed and recommendations for redesign for future space applications are stated.

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1.0 INTRODUCTION AND SUMMARY

The two water electrolysis systems used in the NASA space station simulation 90-day manned test (NASA CR 111881) of a regenerative life support system at the McDonnell Douglas Astronautics Company were refurbished as required and subjected to 26 weeks of testing. The two electrolysis units are both promising systems for oxygen and hydrogen generation and both needed extensive long-term testing to evaluate the performance of the respective cell designs and provide guidance for further development. These units have been considered seriously in the space station prototype environmental thermal control and life support program.

The objective of the program was to test extensively the two systems. The program was structured to subject the units to nominal levels for the first 13 weeks to approximate the essential conditions and requirements of the 90-day test. The second half of the testing was intended to explore some off-nominal conditions. The program was intended to demonstrate the degree of maturity of the two electrolysis systems and to shed light on the status of water electrolysis technology in general and of those two units in particular. The static vapor feed unit (SVFU) used a vapor feed of make-up water and intermittent circulation of electrolyte. The circulating electrolyte unit (CEU) used a liquid supply of make-up water with continuous electrolyte circulation. Testing was conducted to evaluate the performance parameters of current, pressure, variable oxygen demands, and orbital simulation. Performance evaluations included cell voltage variations, mass balance, current efficiency, system problems, reliability and maintainability.

The program was managed by the NASA Manned Spacecraft Center (MSC). The Boeing Company performed in a support-contractor role to the MSC. The McDonnell Douglas Astronautics Company (MDAC) conducted the overall test program and provided the SVFU, which contained cells and modules originally manufactured by Allis-Chalmers Manufacturing Company. Life Systems, Incorporated, performed acceptance testing on the modules of the SVFU and served as a technical consultant to MDAC. The Lockheed Missiles and Space Company (LMSC) manufactured the Circulating Electrolyte Unit (CEU), refurbished and performed acceptance tests on the unit and was responsible for its operation, maintenance, and test analysis.

A test committee composed of the contractors involved and three NASA development centers, the MSC, the Langley Research Center (LaRC), and the Ames Research Center (ARC), controlled the proceedings in order to achieve a high degree of objectivity of the results. Test committee management was adopted to pool capabilities and to allow an interchange of ideas in the event that changes in operating conditions or hardware would be required.

The original test plan called for equivalent operating modes for the two systems. Operation of the SVFU departed significantly from the original test plan, which included variations in production rate and pressure, as well as orbital simulation. Because of SVFU system problems, the test plan was amended to restrict attempted operation to nominal production rates at nominal operating pressure. This would result in 3.63 kg/day (8 lb/day) oxygen production with three modules on line. Accumulator control of oxygen production was used for a period of one week. The circulating electrolyte unit was operated substantially as originally planned throughout the 26 weeks.

A major ground rule of the test was a "hands-off" philosophy in order to preclude interruption of operation and to approximate NASA operational usage by crewmen or relatively unskilled operators in a remote location.

Circulating Electrolyte Unit (CEU)

The circulating electrolyte unit consisted of four electrolysis modules, each of which contained 16 cells connected hydraulically in parallel and divided electrically into two banks with 8 cells each connected in series. Differential-pressure controllers on each module maintained appropriate pressures to effect gas-liquid phase separation. The self-contained unit operated in a completely automatic mode, including startup, shutdown and safety shutdown with limited fault diagnosis. The front panel displayed operating conditions and the safety status of parameters and contained optional manual controls. The unit interfaced with external-power, feed-water, coolant-supply, product-gas lines and also data output signals. The design output of oxygen was 3.63 kg/day (8 lb/day). Oxygen production rate was variable from 0 to 4.54 kg/day (10 lb/day) and both hydrogen and oxygen were discharged at ambient temperature at a pressure of 1.1 x 10^5 N/m^2 (16.2 psia).

Water was fed by direct injection into the potassium hydroxide (KOH) circulating electrolyte loop. The reservoir served in the one-g environment as an accumulator, as a gas separator, and as the water-feed inlet and control. Heat generated by the electrolysis reaction and electrical controls was removed in a heat exchanger located in the thirty percent KOH electrolyte loop. The unit operated at ambient temperature resulting in the generated-gas dewpoints being at or below ambient to preclude the need for liquid condensers/separators and to provide instant startup capability. Pulse-width-modulated power conditioning was used for electrolysis-current control. The oxygen-generation rate was controlled by cycling the current to three of the four modules between 4.5 A (low mode) and 12 A (high mode). These rates corresponded to cell-current densities of 50 and 133 mA/cm^2. The fourth module of this unit was a "standby," programmed to operate continuously at 4.5 A.

An external electronic timing device was used to provide the command signals to the system current-mode-control logic to simulate spacecraft oxygen demands. All necessary operating conditions could be selected with this test device.

The LMSC water electrolysis system operated for approximately 12,400 module-hours during the 14,600 module-hours scheduled for the test program or about 84.6% of the goal and generally met all the operating requirements of the test program. Most of the down-time resulted from troubleshooting of electronics problems. There were no cell or module failures.

The key requirements were to operate reliably and to produce oxygen at the design rate of 3.63 kg/day (8 lb/day) up to the maximum capacity of 4.54 kg/day (10 lb/day). The efficiency of the unit in producing gas was evaluated, although there were no specified requirements on efficiency.

The longest period of uninterrupted operating time was 53 days, from day 130 through day 183. This period could have been longer except that scheduled testing ended on day 183. The unit also operated uninterrupted for 38 days in the first half of testing, from day 51 to day 88. It is important to note that the amount of down time experienced by both units was considerably longer than one would expect with around-the-clock attendance and the provisioning of ample spares. The circulating electrolyte unit was able to maintain required production even at the 4.54 kg/day (10 lb/day) rate during attended operation.

The performance degradation at the 3.63 kg/day (8.0 lb/day) O_2 production rate showed about a 4.5 percent increase in the energy required per 0.45 kg (1.0 lb) of oxygen when compared with the initial value. Most of the observed performance loss was caused by the experimental anodes in module 1. Energy requirements increased approximately 2 percent over the 6 months of operation when considering module 2, 3, and 4 alone (which had the fully developed electrodes). Testing at the maximum oxygen rate of 4.54 kg/day (10 lb/day) produced no significant increase in rate of performance degradation when compared with the 3.63 kg/day (8 lb/day) rate. The initial specific energy requirement was approximately 5 percent higher at the 4.54 kg/day production rate.

A significant result of the testing was the satisfactory performance during the simulated orbital performance of the system (test days 103 through 110). The gas production was cut to zero during the shadow portion of an orbit (38 min.) and production was at design level during the sunlit portion of the orbit (54 min.). During this one-week test period, 120 orbits were simulated, thereby subjecting the system automatically to 120 changes from zero up to maximum oxygen production and 120 step changes from low-mode current to zero. Module specific energy requirements for cyclic operation were 5 percent lower than for continuous operation because of lower cell voltages. No measurable degradation in performance was observed during the one-week test period.

All cells in the CEU module had common electrolyte as a result of the circulating electrolyte concept. As a result, every electrode in the module became a cell with every other electrode creating unwanted cells which opposed the electrolysis reaction. This effect was minimized by designing these paths to have high electrical resistance along the electrolyte path between them. The net effect was that a portion of the current delivered to a module was shunted through the common electrolyte and around the electrolysis cells. This shunting reduced the oxygen and hydrogen production to values 3 to 4% below Faradaic coulomb equivalents.

Current efficiencies for the several operating conditions were determined by comparing the measured oxygen flow (wet-test-meter data) with the Faradaic coulomb equivalence data. The data indicated that current efficiency did not change significantly with operating time and that it increased slightly at higher production rates. Although the difference is not significant considering the data scatter, it did show the correct trend, assuming that shunt current losses were constant and independent of production rate.

Analysis of product gases was performed 14 times during the testing. Nitrogen was detected in the O_2 samples only 3 times at a maximum value of 0.5% and in the H_2 samples 7 times at a maximum value of 1.75%. It is believed that this high value, which was detected only once, was caused by air in the sample. If the sample is eliminated as bad data, the maximum N_2 detected in the H_2 sample was 0.71%. Hydrogen was never detected in the O_2 samples. Oxygen was detected four times in the H_2 samples at a maximum level of 0.15%. Only one organic peak was detected by the gas chromatograph at the level of 1 to 2 parts per million. This was traced to two solenoid valves which were added to the system without proper cleaning to remove a Teflon spray and mineral oil which the manufacturer normally used on some of the parts. This peak gradually disappeared over a six-week period.

Analysis was conducted to determine the amount of KOH carryover from the electrolysis system. This was done by monitoring the pH change of water in the bubbler downstream of the unit. Carryover caused the pH of the water in the O_2 bubbler to change from 6.7 to a maximum of 11.85. The rise was rapid in the first 3 weeks (to 10.50) then leveled off over the next 12 weeks to the maximum of 11.85 and then a gradual decline to 10.5 at the end of the 26-week test period. The pH change in the H_2 bubbler was significantly less. A maximum of 9.75 was reached after 4 weeks of testing, then it gradually declined to 8.90 at the end of testing. Analysis of the amount of KOH carryover required to change the pH of the bubbler water showed that less than 0.09 gram of KOH was carried over from the unit to both bubblers combined.

By the end of the testing, the circulating electrolyte unit had experienced 22 failures. The majority of these failures occurred early in the testing and no failures occurred after test day 130.

A total of five failures occurred in the circulating electrolyte unit that were caused by design deficiencies. Three of these failures were caused by broken plastic plumbing fittings in the circulating loop. One failure was caused by a pressure decay, the result of a non-optimized startup sequence; and one failure was the result of system self-restart in an improper mode after a momentary power loss. All of these design deficiencies were eliminated during the course of the test. The CEU had no cell or module failures during the test. It is judged that all remaining circulating electrolyte unit system failures (17) would have been eliminated by a flight-article quality-assurance program and by the use of high-reliability electronic components.

The majority of the system shutdowns were caused by intermittent electronic noise which triggered the master integrated circuit that commanded automatic safety shutdown. The problem was difficult to diagnose because it was intermittent. Circuitry changes and electronic component replacement eventually corrected the problem.

Static Vapor Feed Unit (SVFU)

The SVFU operated at moderate temperature and pressure to achieve high performance levels and to provide required mass transfer characteristics. Water feed was by vapor diffusion across the hydrogen cavity to the electrodes. Vapor diffusion served to remove contaminants in the liquid reactants, to reduce the distance between electrodes, and to isolate the cell electrolyte. Each cell was composed of three compartments: an electrolyte-feed cavity, a hydrogen cavity and an oxygen cavity. Compartment separation and liquid-vapor phase separation were achieved by asbestos sheets with appropriate support. The cathode-asbestos-sheet-anode assembly contained captive potassium hydroxide (KOH) electrolyte. Water was fed to this assembly by vapor diffusion across the hydrogen cavity. The 35% KOH in the water loop is provided to act as a vapor pressure depressant. As a result small changes in electrolyte concentration produce relatively large changes in vapor pressure differentials across the two cell matrices. The normal operating pressure of the cell was 3.1×10^5 N/m^2 (45 psia) and the operating temperature was in the range from 350° to 367° K (170 to 200°F).

Two different types of cells were used in the SVFU during the test program. These were designated the 1968 cell design and the 1970 cell design. The 1968 design contained a porous Teflon membrane between the electrolyte-feed cavity and the hydrogen cavity. The 1970 design cell did not contain this membrane but did include larger diameter holes in both feed-matrix perforated sheets. Both of these features enhanced water-vapor feed-rate capabilities in the 1970 cells. The 1970 cells also contained a porous nickel plaque in the anode compartment to increase cell tolerance to transient changes in electrolyte volume. The 1970 cell was approximately 10 percent thicker than the 1968 design.

Normally, thermal control was passive with heat removal by evaporation of water into the product gases and by convection and radiation from the module. Resistance heaters were imbedded in each cell and in the module end-plates to bring the system to temperature at startup, to maintain minimum temperatures at low current densities, and to recover operating temperature after electrolyte circulations.

Each electrolysis module contained 15 cells connected in series, electrically, and arranged in parallel, hydraulically. Feed water was supplied to each module on a pressure-demand basis. A pressure regulation system maintained total operating pressure and gas-to-liquid differential pressures for liquid-vapor phase separation in the modules and in the water condensation loop.

Electrolyte was pumped through the circulation loop and modules every 6 hours. A number of other modes of operation were also possible. Circulations were performed to remove trapped gases from the modules and to restore KOH concentration balance distorted by the trapped gases and by uneven mixing of feedwater and KOH. Solenoid valves isolated the modules from the electrolyte loop except when the pump was programmed to purge that particular module.

Other important components of the static vapor-feed system were the condenser and liquid/gas separator. Three modules were needed to produce the design-rate of oxygen, but the breadboard system could operate with one, two, or three modules. The system interfaced with the data acquisition and control system, which had the capability to shut down total SVFU or individual modules when selected parameters went out-of-tolerance. In the normal operating configuration (three electrolysis modules), design oxygen production was 3.63 kg/day (8 lb/day) when operated at a current of 11.4 amperes. The maximum planned production was 4.54 kg/day (10 lb/day). The nominal oxygen and hydrogen discharge conditions downstream of the condenser/separator were 3.1×10^5 N/m^2 (45 psia) at ambient temperature and a dewpoint of approximately 292 K (66°F).

Current to each electrolysis module was regulated by one of three methods, depending on the mode of operation selected. Normally, a current-control potentiometer fixed the current to the module. During analog control, the current was regulated by sensing the oxygen accumulator pressure downstream of the unit to adjust the production rate to meet system demands. Automatic current control for the orbital duty cycle was provided but not used. Current to each module was adjustable from 0 to 15 A (0 to 130.0 mA/cm^2) with the design operation point at 11.4 A (99.0 mA/cm^2).

The static vapor-feed unit (SVFU) was disassembled from the packaged configuration that was used in the 90-day test. Components were remounted on a breadboard structure so that all equipment, plumbing, controls, and displays would be readily visible and available for maintenance. This was accomplished because there were extensive problems with peripheral components in the 90-day test. The overall purpose of the refurbishment of the unit was to improve the reliability of the total system. Modules and cells were refurbished to regain operating capability. Refurbishing all fluid flow hardware and electronic hardware was accomplished to obtain improved performance, high reliability, more versatility, and data for long life performance. These changes were expected to eliminate failures due to faulty equipment and concentrate efforts on verifying cell and module design limits and capabilities.

Two separate acceptance tests were conducted on the SVFU modules. The first was immediately after refurbishment at the Allis-Chalmers facility. This period of performance was for 48 continuous hours. All modules successfully completed this test without any shutdown due to out-of-tolerance cell voltages. Operations were conducted at current levels of 5, 8 and 12.4 amperes. Cell voltages remained at a level less than 1.60 volts for all modules at the 12.4 ampere current level. Electrolyte circulation was continuous. Temperatures were maintained at 350° to 353° K (170° to 175° F). Electrolyte concentration was 35% and system pressure averaged 6.89×10^4 N/m^2 (10 psig).

The second acceptance test effort was conducted for 100 continuous hours by Life Systems, Inc. (LSI). The conditions of operation were at the nominal design conditions projected for the subsequent 26-week performance/endurance testing. During the acceptance testing no individual cell of any module exceeded the prescribed upper limit of 1.7 volts. All other operating parameters were also held within prescribed limits. Electrolyte at 35% concentration was circulated continuously. The collected data indicated that maximum voltage never exceeded 23.9 volts per module, which is equivalent to 1.59 volts per cell average. The module with the highest module voltage over the 100 hours of operation was module 1. Its voltage, however, remained constant at 23.9 for the last 50 hours of acceptance testing. The best performer was module 2. Its voltage remained between 23.0 and 23.5 volts throughout the 100 hours of testing. The range of module voltage for all 5 modules was 23.0 to 23.9 volts resulting in average cell voltages of 1.53 to 1.59 volts, respectively. Some evidence of external leakage was observed on two of the modules and stray electrolysis was also observed. Neither of these problems prevented completion of any acceptance or characterization testing on the modules.

Characterization tests at LSI indicated that operation of the 1968 design cell was limited to 15 amperes or less. The 1970 design cell had a greater tolerance for operation at increased current densities. This improvement was attributed to increased mass transfer permitted by not having a Teflon membrane between the electrolyte feed asbestos sheet and the hydrogen-side perforated sheet and larger diameter holes in both feed matrix sheets.

Two separate checkout tests were conducted on the SVFU. The first test was a 100-hour test that was conducted at the end of refurbishment and system integration. The second was termed the 80-hour checkout test. The major difference between the two tests was the method of water feed. In the 100-hour test the water was supplied on a pressure demand principle directly into the intermittently operating electrolyte circulation loop. In the 80-hour test the water was supplied on a pressure demand principle directly into the water cavity manifold of each module. Also circulating pump operation frequency was 30 seconds each 30 minutes in the 100-hour test and 2 minutes each 6 hours in the 80-hour test. The 100-hour test utilized module 1 only and the 80-hour test used 3 modules.

During the 100-hour period the system operated at 6.89×10^4, 20.6×10^4 and 34.4×10^4 N/m^2 gage (10, 30, and 50 psig) and 6, 10 and 14 amperes. At the 20.6×10^4 N/m^2 gage (30 psig) level the system also operated at 0.5 and 11.3 amperes under special conditions. These special conditions included analog control of current by a rise and fall of pressure in an oxygen accumulator tank and simulation of orbital operations by having nominal current levels during sunlight portion of the orbit (53 minutes) and 0.5 amperes current during the night portion of the orbit (40 minutes). Periods of performance at any operation varied from a minimum of 8 hours to a maximum of 16 hours. A number of shutdowns occurred but were mostly attributable to human error and shortcomings in procedural evolutions. Shutdowns due to excessive cell voltage or module voltages did not occur. Indicated problem areas included: a) separator vent sequence procedures; b) current controller electronics affected by condensation; c) stray electrolysis in the electrolyte loop; and d) settings of the differential pressure switches.

A number of problems were encountered in the 80-hour test that necessitated a number of modifications to the system and revision to the schedule for the test. Some of the shutdowns that occurred could be solved by improved operator performance and mechanical changes. The major unsolved problems were the cause of overvoltage in the cells, KOH accumulation within the H_2 cavity and identification of the proper electrolyte concentration to be used in the modules and the system. All of these appeared to be related to electrolyte maldistribution.

The original module manufacturer consistently tested the module performance with continuous circulation of electrolyte. Requirements of this test called for intermittent circulation with distilled water being supplied directly to the modules when the circulation pump was not operating. Distilled water was supplied to the circulating loop in the original design. Pretest analysis showed that when distilled water was supplied directly to the module the concentration of potassium hydroxide within the cells would vary from cell to cell depending on its distance from the feed water connection. Cell number 1 would receive more KOH than cell 15 because of the long flow path from the feed water connection. Cell 15 would have a final concentration of 32.7% when the initial loop concentration was 30% and cell 1 would have a final concentration of 35.2% with 10 cc of plumbing external to the module. The selected mode of operation was to provide the module with the center cells at 35%. Thus, an initial charge of 31% was used. In order to isolate the loop electrolyte from the feed water, check valves were installed in the loop line upstream of the inlet to the modules. This proved unsatisfactory as the check valves were not all identical and cross feeding of electrolyte between modules, on the discharge side, began to effect performance.

The plumbing was modified to place the check valves at the electrolyte outlet to the module to prevent back feeding. Also the isolation solenoid valves at the module inlet were rewired to be closed at all times except when the circulation pump was operating. This improved performance but not enough to gain long-term operation. After numerous tries with operating periods of 2 to 8 days, the check valves on the discharge line of the modules were removed and checked for leaks. All three module check valves had slow steady leaks when held in a horizontal position with less than one foot of liquid head; the condition existing when installed in the system. Thus, back feeding of electrolyte between the modules and the electrolyte circulating loop still existed.

The next change was to replace the check valves with solenoid valves to completely isolate a module from the electrolyte loop and the other modules. When this was accomplished, the performance was improved and the system would operate 6 to 12 days. Some other characteristic of electrolyte flow was affecting performance.

Analysis of the collected data revealed that cell 15 was changing the most over a given period of time. Cell 14 was increasing in voltage only slightly over the same period of time and the rest of the cells showed essentially zero change. Ordinarily the distilled feed water enters the bottom of the module and follows a manifold which connects to all cells. Bench testing with plastic tubing simulating the configuration of 4 cells and two fluids of different specific gravities revealed that most of the distilled water was rising in cell 15's water cavity, flowing across the top of the module in a common manifold and then entering into the adjacent cells. The excess flow of water through the water cavity of cell 15 was causing an adverse distribution of electrolyte within the cell and hence high cell voltages.

Two attempts were tried to eliminate this undesirable gravitational affect. The first was to operate the module with the water feed at the top. This did not produce any improvement in duration of operation and did cause the module to operate at a significantly higher module voltage. It was thought that the gas accumulating in the cells was restricting the flow of distilled water into the module manifold thus causing high cell voltages due to a low feed rate. The second attempt was to disconnect cell 15 electrically and to use the cell as a liquid bypass line. This also did not prove beneficial, as cell 14 reacted with high cell voltage even faster than cell 15 did originally. This problem of electrolyte maldistribution still remains to be solved.

Although electrolyte distribution caused problems and kept continuous module operating durations relatively short, meaningful data was collected relative to the concept of static vapor feed electrolysis. The SVFU operated for approximately 6550 module hours during the 13104 module-hours scheduled for the test program or about 50% of the goal. As noted earlier, this performance record could have been improved by around-the-clock attendance and ample spares provisioning. The SVFU did require extensive labor on cell and module repair to bring it back to design gas-production capability. Operation of the unit at 4.54 kg/day (10 lb/day) production rate was not attempted in the interests of achieving stable operation at the design conditions.

The unit was able to maintain the required production rate of 3.63 kg/day (8 lb/day) for only 2 days with 3 module operation and only 13 days with 2 module operation. During all other periods the modules were a) operating at reduced capacity; b) experiencing malfunctions; c) undergoing troubleshooting to correct problems; or d) shutdown. Analog control of system current was conducted with limited success during test days 8 through 15. Success was limited because of electrolyte maldistribution problems and the modules were not all operating at uniform conditions.

A mixture of 1970 and 1968 design modules were used during the first 44 days. These modules were operated at 11.3 amps. Energy requirements were higher in this period because each 1970 module O_2 production rate was reduced by 0.113 kg/day as a result of shunt currents induced by electrolyte bridging across the hydrogen cavity. Electrolyte bridging meant that there was a direct liquid-liquid contact between the active cell electrolyte and the feed-cavity electrolyte. Due to the frequent shutdowns and flushing of the modules, specific performance degradation could not be determined. During intermittent circulation at nominal production, parasitic power represented approximately 16% of the total power requirements with 3 modules and 22% with 2 modules. Parasitic power comsumed 43% of the total power during continuous circulation because of increased cell heater operation and circulation pump operation.

Analysis of product gases was performed 13 times during the testing. Nitrogen was detected in the O_2 sample only 3 times at a maximum value of 0.7% and in the H_2 sample 5 times at a maximum value of 1.34%. It is believed that this high value (the first sample taken) was caused by air in the sample. If this sample is eliminated as bad data the maximum N_2 detected in the H_2 samples was 0.52%. Hydrogen was never detected in the O_2 samples. Oxygen was detected four times in the H_2 samples at a maximum level of 0.08%. Organic contaminants were never detected in either the O_2 or H_2 samples.

Analysis was conducted to determine the amount of KOH carryover from the electrolysis system. Carryover caused the pH of the water in the O_2 bubbler to change from 6.7 to a maximum of 10.8. One reading was higher but it was discounted because liquid carryover had occurred due to system failure. The rise was rapid in the first few weeks, then a leveling off occurred. The level stayed essentially constant at 10.60 for the last 16 weeks. The pH in the H_2 bubbler rose to 9.2 within 3 weeks of startup and then varied between 8.8 and 9.4 for the remainder of the test period.

By the end of testing, the SVFU had experienced a total of 59 failures. The majority of these failures occurred in the first half of the test. The majority of the failures that occurred in the last half of the test were due to electrolyte maldistribution.

The comparatively low failure rate achieved during the first 25 to 30 days of operating time of the SVFU was achieved using modules of mixed designs. Eventually, this configuration was determined to be unrealistic because under the operating conditions used, it had inherent defects such as uncontrolled transfer of electrolyte between modules due to leaking check valves, excessive stray electrolysis, electrolyte bridging and shunt current losses. Between day 30 and day 90, the SVFU was operated in a series of modes necessary to solve electrolyte-distribution problems within the 1968 design modules, to stabilize gas-to-liquid differential pressures, to replace the accumulator with an improved design after a failure and to incorporate a one-g gas-liquid separator. The unit was operated with continuous electrolyte circulation and generally at 70 percent of nominal current density while awaiting parts for final redesign between day 90 and day 120. Operation after day 120 was representative of the system in the most favorable mode found. Failures occurring during this period were caused by fatigue cracks in the polysulfone structure of the cell or by undesirable electrolyte-concentration gradients within the modules. These two failure modes persisted despite various attempts to control and limit their effect. It was judged that neither of these failure modes would be eliminated by continuing testing under the ground rules of this test program.

The program provided extensive testing of the refurbished 90-day electrolysis systems. Sufficient data were generated to ascertain the design maturity of each system and perhaps of electrolysis in general. It was also concluded that the water-electrolysis technology at the system level is quite weak. Electrolysis power controllers were found to consume large quantities of power. A properly developed controller would be required to operate efficiently at a wide range of module power requirements and power-supply characteristics.

The circulating-electrolyte water electrolysis system was demonstrated to be quite sound basically. Generally, the system operated as intended and proved its versatility by successfully operating at all the conditions planned for it in this test program. Control logic for the circulating-electrolyte unit was highly developed as demonstrated by the completely hands-off operation, the automatic startup/shutdown feature and by the automatic safety shutdown capability. The lack of high-reliability components and the lack of application of rigorous quality control created most of the problems. The problems encountered seemed to be understandable and amenable to solution.

The static vapor-feed concept demonstrated a high performance potential when it operated. The basic problem was to keep it operating. The major problem defying solution at the end of testing was adequate control of the distribution of feed water and electrolyte in the feed cavities and manifolding.

The static vapor-feed unit tested under the present program had eliminated many of the shortcomings of the peripheral system equipment and design that were inherent during the 90-day manned test program. Operation was still limited by the existing modules, in particular by electrolyte-distribution problems, by KOH back-diffusion limitations, and finally, by restrictions of the vapor-feed rate due to mechanical obstruction. The module and cell problems were not caused by conceptual limitation.

2.0 PROGRAM OBJECTIVES AND REQUIREMENTS

2.1 Objectives

The general objective of the program was to test extensively the two water electrolysis systems that had been used in the space station simulator 90-day manned test of a regenerative life support system. The test history of both units in the 90-day test showed certain weaknesses which were not consistent with long-duration, trouble-free operation. (1,2)* The systems were repaired, refurbished, and modified only to the extent that was felt to be required to meet the overall test objectives of a short-term readiness test followed by a 26-week test program of endurance and performance evaluation. Both were development systems and, therefore, did not have requirements for high-reliability electronic components or rigorous quality control. System changes to increase performance capabilities were not made unless the changes were required to meet the test objectives.

Within the scope of the general objective certain specific objectives, relative to water electrolysis systems, long life technology, automatic monitoring and life support systems, were also identified and evaluated during the testing periods. These specific objectives include:

- Conduct unbiased evaluation of two different types of water electrolysis systems.
- Advance the technology related to water electrolysis systems in general and identify improvements for future designs.
- Prove the worth of two different type electrolysis cells; vapor feed with intermittent electrolyte circulation, and liquid feed with continuous circulation.
- Demonstrate automatic monitoring and safe-control capability of a total system.

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* Numbers in parentheses indicate references listed in Section 8.0.

2.2 Requirements

The preparation, assembly, integration, and execution of this test program was conducted over approximately a 13-calendar month period. The effort covered review of acceptance testing of both electrolysis units at manufacturer and supplier facilities, final integration of test units into the test stand, documentation preparation, long-term testing and detailed reporting. Endurance testing was to constitute as many days as practicable within the 26 calendar weeks of testing. Preceding the endurance testing was approximately 3 1/2 months of documentation preparation, acceptance testing at supplier facilities, system installation and checkout. Following the endurance testing was approximately 3-1/2 months for report preparation, approval and publication.

Originally, this program was structured to subject the units to nominal loads for the first 13 weeks to approximate the essential conditions and requirements of the 90-day test. The second half of the testing was intended to explore some off-nominal conditions. This program was intended to demonstrate the degree of maturity of these two water electrolysis systems and to shed light on the status of water electrolysis technology in general and of these two units in particular.

Emphasis during this test program was directed to development requirements in support of breadboarding and testing intended to expose design deficiencies before they reach the manufacturing or operational phase of the project. The contractor was to identify any problems which became evident and might potentially affect manufacturing processes and techniques. An attempt was made to identify solutions to the problems encountered and further identify what must ultimately be developed in order to facilitate manufacturing of the end product. It was also the intent of this program to determine the operating limits, capabilities and overall potential of these concepts for hydrogen and oxygen generation.

3.0 TEST PROGRAM

The two water electrolysis systems were operated in parallel under normal conditions for a period of 26 consecutive calendar weeks. Both units were made to operate for as many days as practicable during the 26 calendar week period to determine life expectancy and measure performance of the two different cell design concepts: static vapor feed and circulating electrolyte.

3.1 System Descriptions

3.1.1 Circulating Electrolyte Unit

The electrolytic oxygen generator, shown in Figure 3-1, was substantially in the same overall configuration as that which was used in the 90-day test.

The CEU operated at ambient temperature and pressure providing rapid startup and shutdown capability. Feed water was injected into the electrolyte which was continuously circulated through the center of the cell providing direct liquid reactant feed to the electrodes.

Two different kinds of anodes were used in the CEU electrode assemblies. Module 1 contained new anodes consisting of a platinum catalytic expanded nickel screen attached to the rim by means of overlapping spot welds. All other electrodes were generally similar except they contained American Cyanimid electrode material secured to the support screen by spot welds. The cells were arranged cathode-anode-anode-cathode-cathode, and so forth, so that each internal gas spacer served two adjacent cells. Outside dimensions of a unit cell were 14.1 by 14.1 cm (5.5 by 5.5 in). The cell thickness was 1.1 cm (0.43 in). The active area of each electrode was 90 cm^2 (14 in^2). A cutaway view of a typical cell is shown in Figure 3-2.

The electrodes used in modules 2, 3, and 4 and the cathodes used in module 1 had more than 5000 hours operating time prior to this test program. The anodes in module 1 were of an experimental design that had undergone limited development.

The oxygen generating unit consisted of four electrolysis modules, each of which contained 16 cells connected hydraulically in parallel and divided

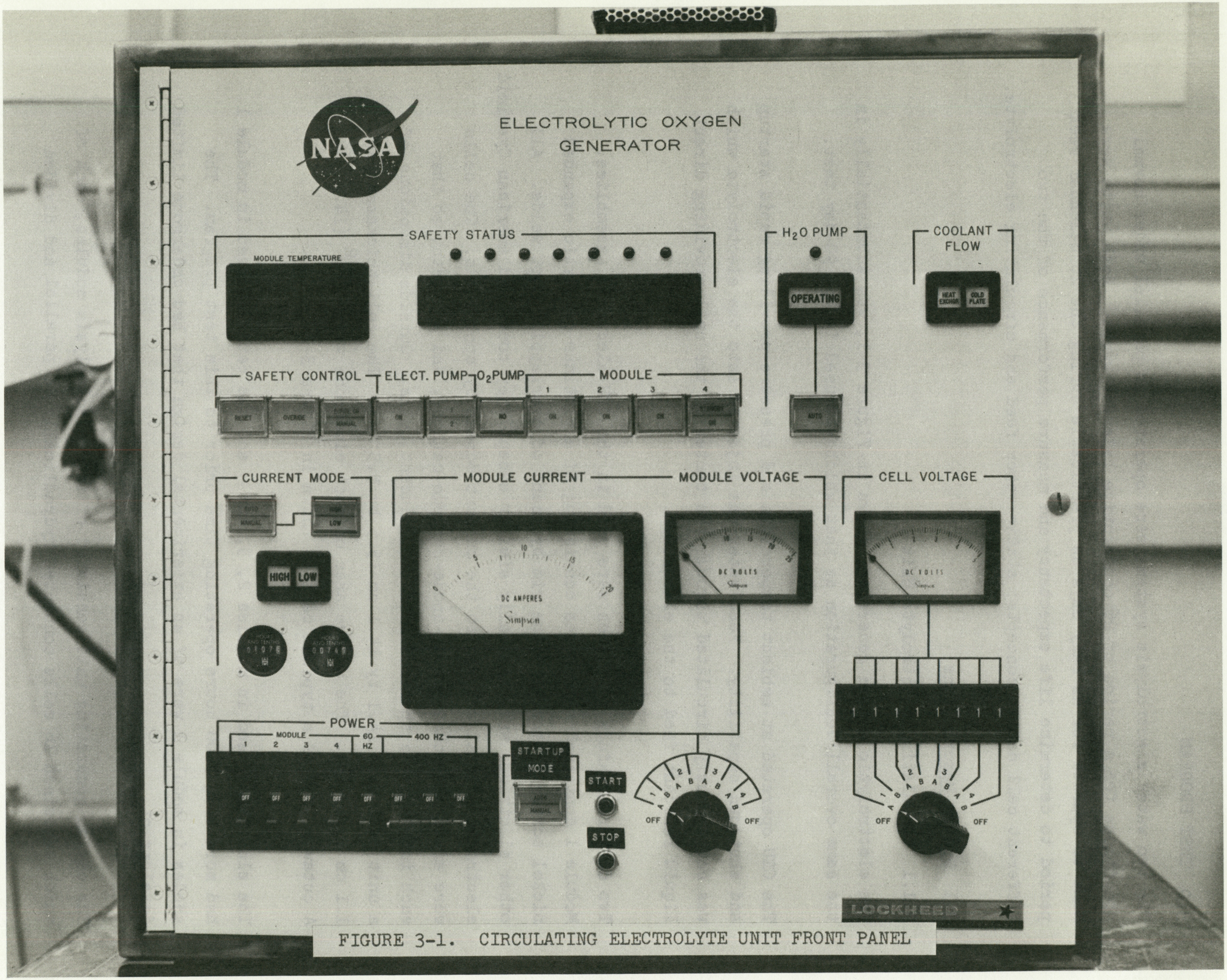


FIGURE 3-1. CIRCULATING ELECTROLYTE UNIT FRONT PANEL

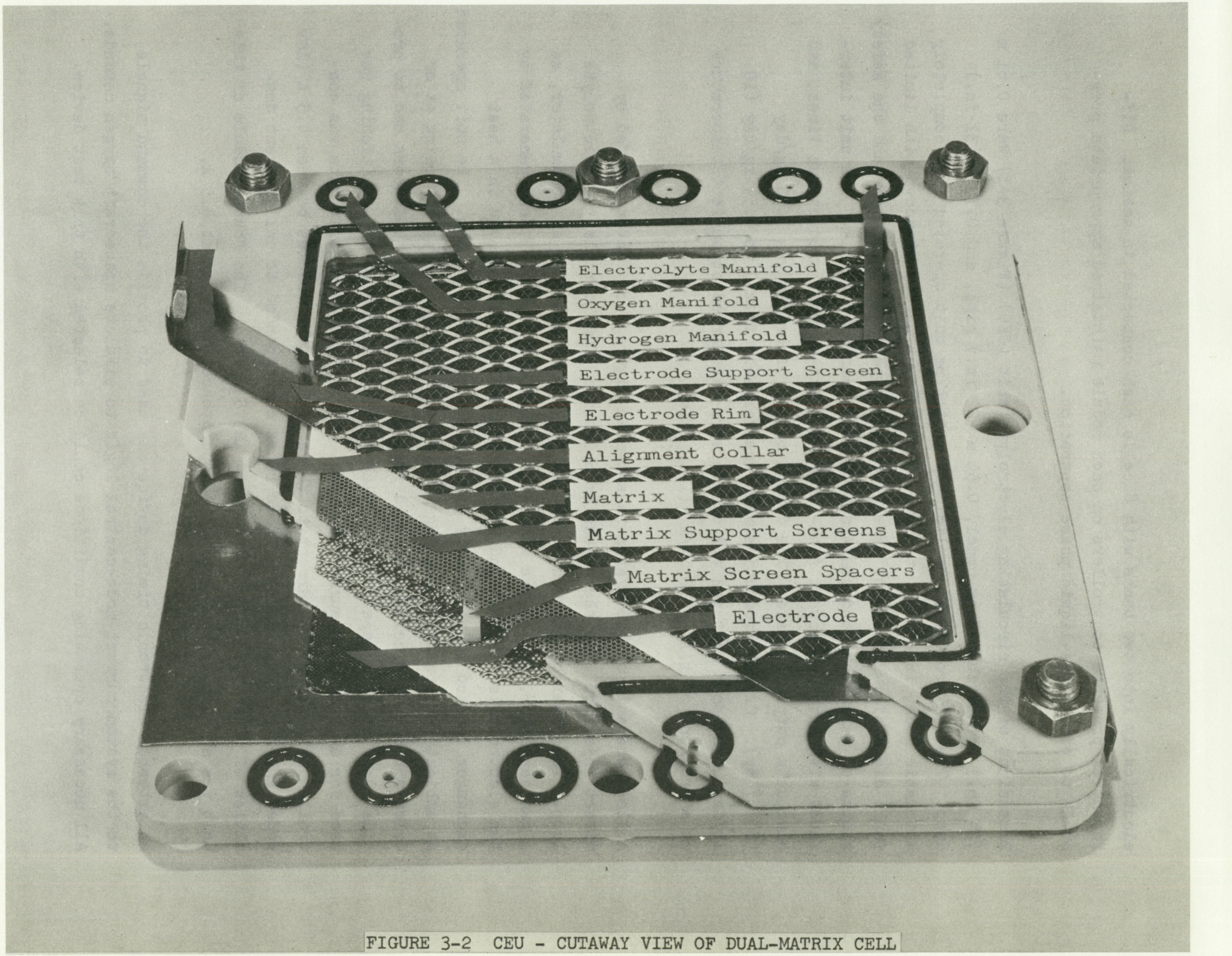


FIGURE 3-2 CEU - CUTAWAY VIEW OF DUAL-MATRIX CELL

electrically into two banks with 8 cells each connected in series. Differential-pressure controllers on each module maintained appropriate pressures to effect gas-liquid phase separation.

Dimensions of the circulating electrolyte unit (CEU) (Figure 3-1) were 0.61 m (24 in.) across the front panel, 0.56 m (22 in.) high, and 0.79 m (31 in.) deep. The self-contained preliminary prototype unit operated in a completely automatic mode, including startup, shutdown, and safety shutdown with limited fault diagnosis. The front panel displayed operating conditions and the safety status of parameters and contained optional manual controls. The unit interfaced with external-power, feed-water, coolant-supply, product-gas lines, and also data output signals. The design output of oxygen was 3.63 kg/day (8 lb/day). Oxygen-production rate was variable from 0 to 4.54 kg/day (10 lb/day), and both hydrogen and oxygen were discharged at ambient temperature at a pressure of 1.11×10^4 N/m^2 (16.2 psia).

A flow schematic of the system is shown in Figure 3-3. Water was fed by direct injection into the potassium hydroxide (KOH) circulating electrolyte loop. The reservoir served in the one-"g" environment as an accumulator, as a gas separator, and as the water-feed inlet and control. Heat generated by the electrolysis reaction and electrical controls was removed in a heat exchanger located in the thirty percent KOH electrolyte loop. The unit operated at ambient temperature resulting in the generated-gas dewpoints being at or below ambient to preclude the need for liquid condensers/separators and to provide rapid startup capability. Pulse-width-modulated power conditioning was used for electrolysis-current control. The oxygen-generation rate was controlled by cycling the current to three of the four modules between 4.5 A (low mode) and 12 A (high mode). These rates corresponded to cell-current densities of 50 and 133 mA/cm^2 (46.5 and 123.5 A/ft^2). The fourth module of this unit was a "standby," programmed to operate continuously at 4.5 A.

An external electronic timing device was used to provide the command signals to the system current-mode-control logic to simulate spacecraft oxygen demands. All necessary operating conditions could be selected with this test device.

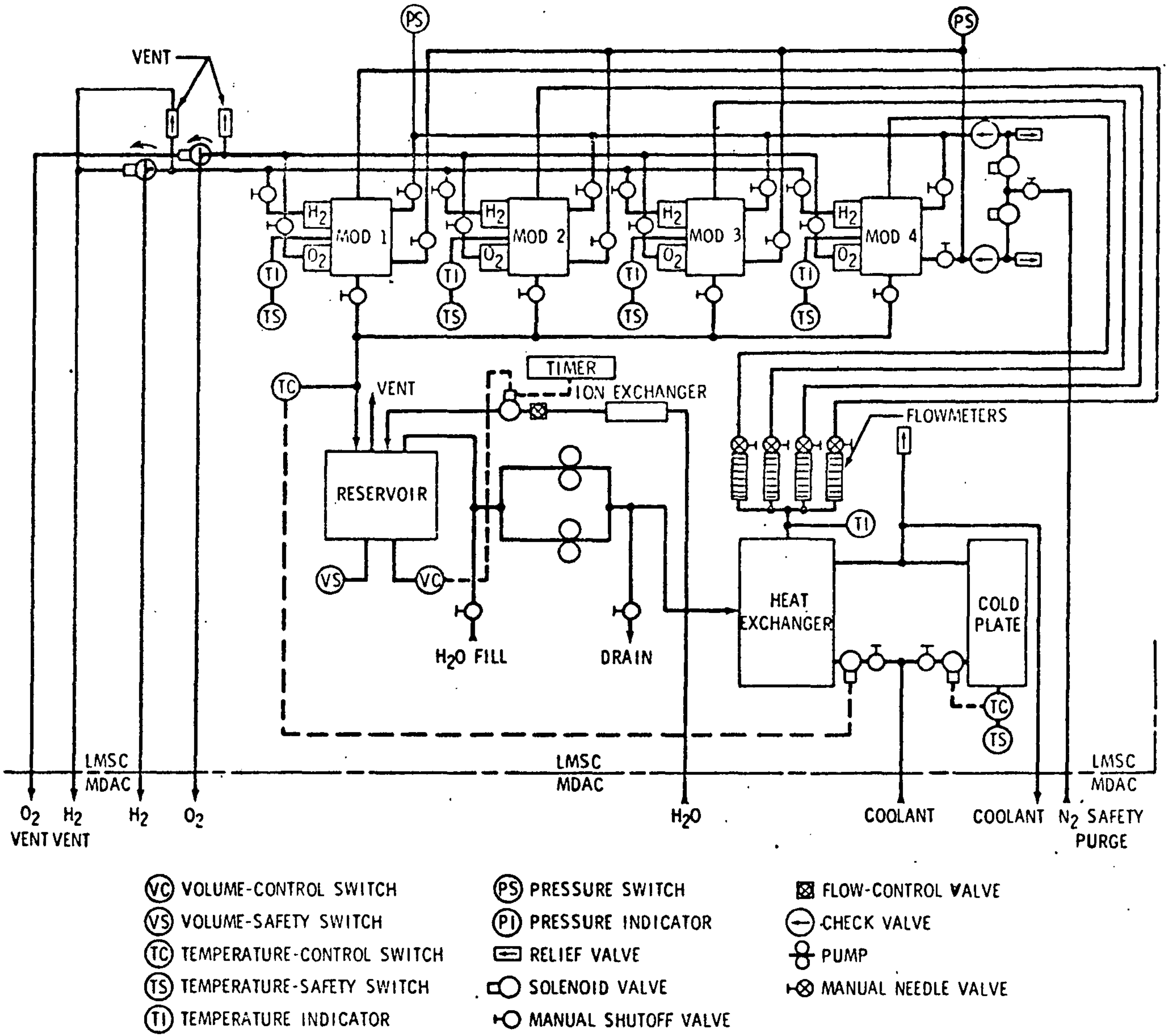


FIGURE 3-3. CIRCULATING ELECTROLYTE UNIT SCHEMATIC

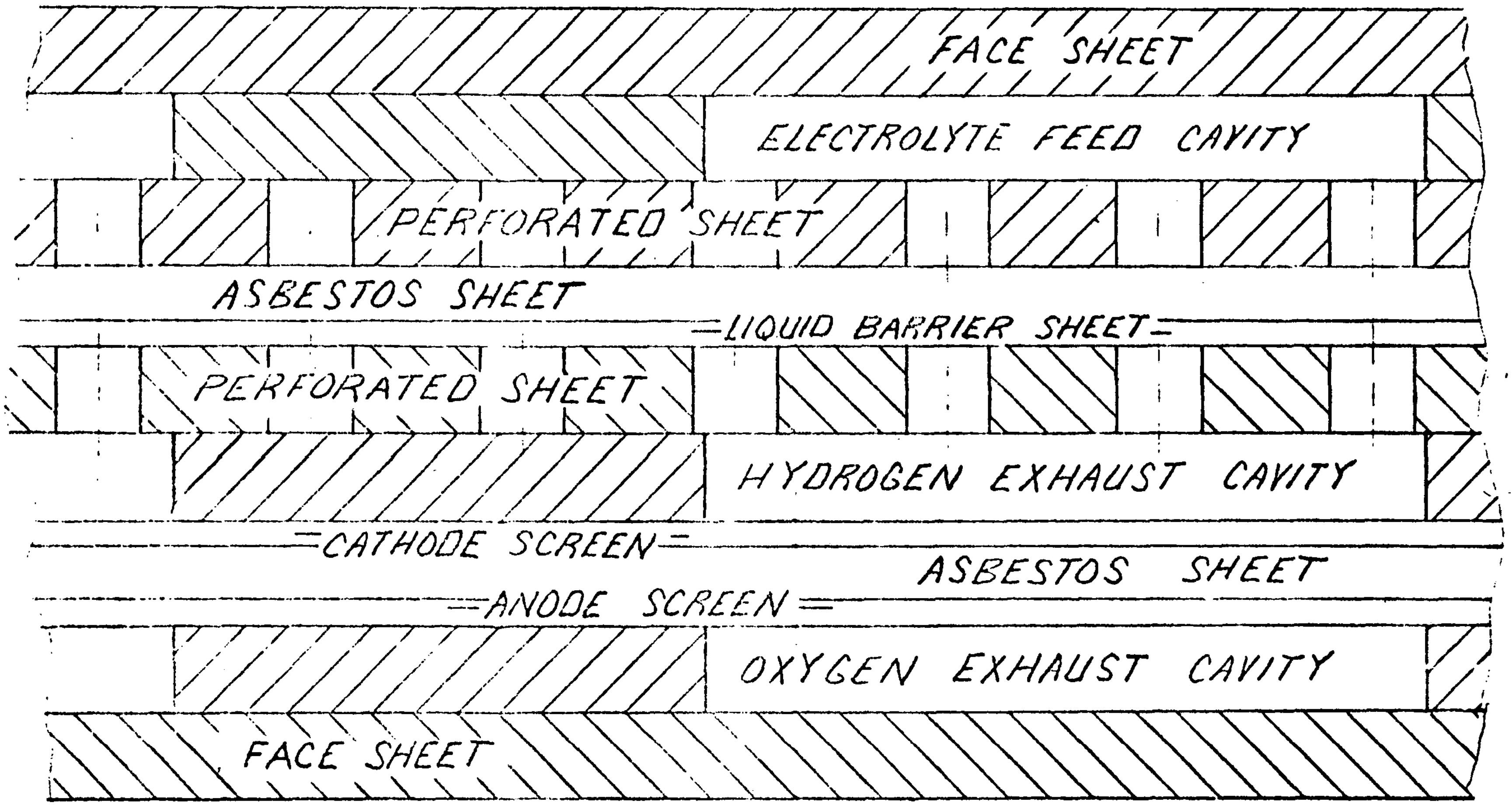
3.1.2 Static Vapor-Feed Unit

The static vapor-feed unit (SVFU) was disassembled from the packaged configuration that was used in the 90-day test. Components were remounted on a breadboard structure, so that all equipment, plumbing, controls, and displays would be readily visible and available for maintenance. This was accomplished because there were extensive problems with peripheral components in the 90-day test. The SVFU operated at moderate temperature and pressure to achieve high performance levels and to provide required mass transfer characteristics. Water feed was by vapor diffusion across the hydrogen cavity to the electrodes. Vapor diffusion served to remove contaminants in the liquid reactants, to reduce the distance between electrodes, and to isolate the cell electrolyte.

Each cell was composed of three compartments: an electrolyte-feed cavity, a hydrogen cavity and an oxygen cavity. Compartment separation and liquid-vapor phase separation were achieved by asbestos sheets with appropriate support. The cathode-asbestos sheet-anode assembly contained captive potassium hydroxide (KOH) electrolyte. Water was fed to this assembly by vapor diffusion across the hydrogen cavity. A cross section of these cells is shown in Figure 3-4.

The overall dimensions of the cells were 13.3 by 20.3 by 0.86 cm (5.25 by 8.0 by 0.34 in). The normal operating pressure of the cell was 31.0×10^4 N/m^2 (45 psia) and the operating temperature was in the range from 350° to 367° K (170 to 200° F).

Two different types of cells were used in the SVFU during the test program. These were designated the 1968 cell design and the 1970 cell design. The 1968 design contained a porous Teflon membrane between the electrolyte-feed asbestos sheet and the hydrogen-side perforated sheet. The 1970 design cell did not contain this membrane but did include larger diameter holes in both feed-matrix perforated sheets. Both of these features enhanced water-vapor feed- rate capabilities in the 1970 cells. The 1970 cells also contained a porous nickel plaque in the anode compartment to increase cell tolerance to transient changes in electrolyte volume. The 1970 cell was approximately 10 percent thicker than the 1968 design.



CROSS-SECTION OF VAPOR FEED
ELECTROLYSIS CELL

FIGURE 3-4

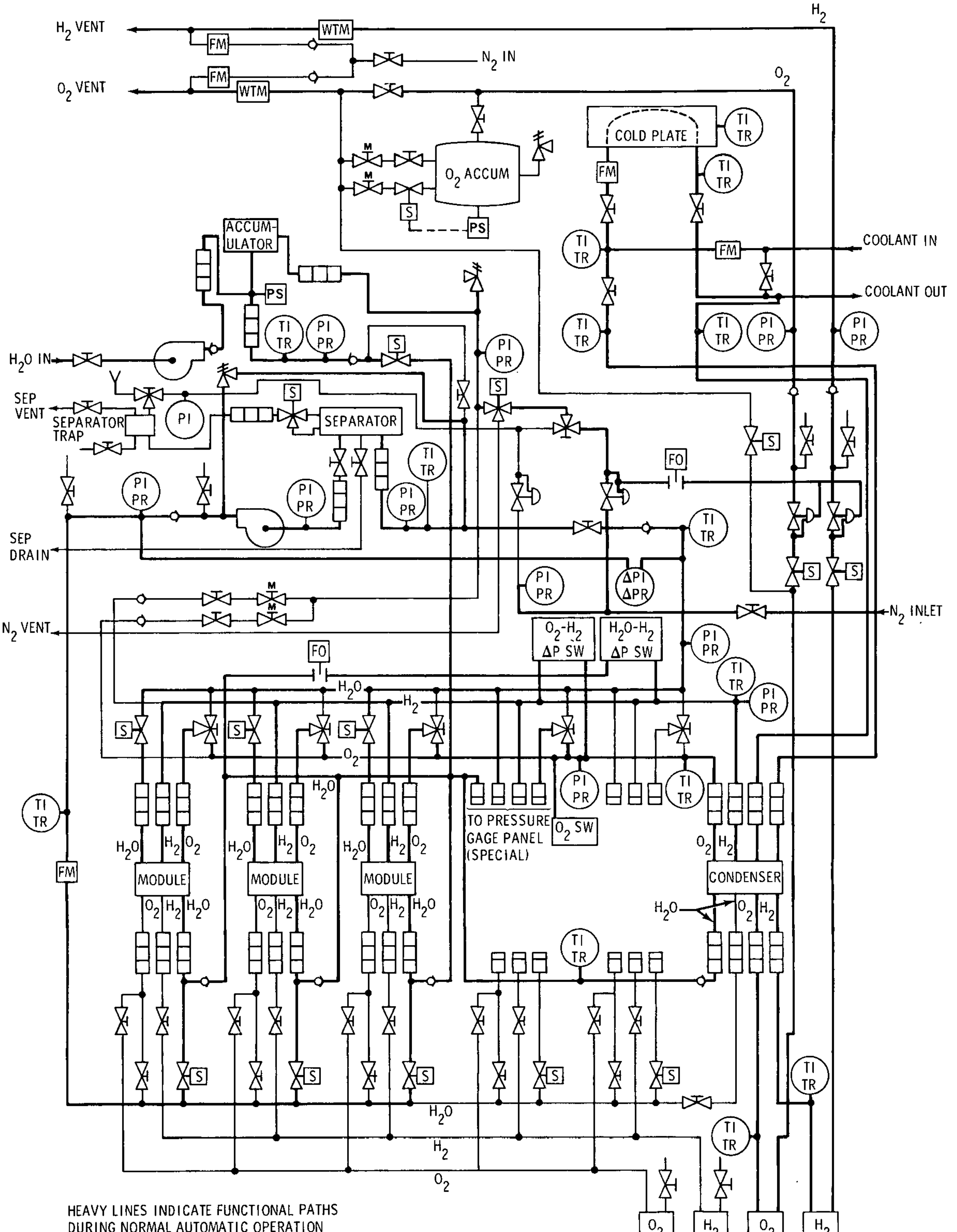
Normally, thermal control was passive with heat removal by evaporation of water into the product gases and by convection and radiation from the module. Resistance heaters were imbedded in each cell and in the module end-plates to bring the system to temperature at startup, to maintain minimum temperatures at low current densities, and to recover operating temperature after electrolyte circulations.

Each electrolysis module contained 15 cells connected electrically in series and arranged hydraulically in parallel.

A complete mechanical schematic of the SVFU is shown on Figure 3-5 and a simplified schematic of the system and single cell is shown in Figure 3-6. Feed water was supplied to each module on a pressure-demand basis. A pressure regulation system maintained total operating pressure and gas-to-liquid differential pressures for liquid-vapor phase separation in the modules and in the water condensation loop.

Electrolyte was pumped through the circulation loop and modules every six hours. A number of other modes of operation were also possible. Circulations were performed to remove trapped gases from the modules and to restore KOH concentration balance distorted by the trapped gases and by uneven mixing of feedwater and KOH. Solenoid valves isolated the modules from the circulating-electrolyte loop except when the pump was programmed to purge that particular module.

Other important components of the static vapor-feed system were the condenser and liquid/gas separator. Three modules were needed to produce the design-rate of oxygen but the breadboard could operate with one, two, or three modules. A photograph of the SVFU is shown in Figure 3-7 and a close-up view of the control panel is shown in Figure 3-8. The system interfaced with the data acquisition and control system, which had the capability to shut down the total SVFU or individual modules when selected parameters went out of tolerance. In the normal operating configuration (three electrolysis modules), design oxygen production was 3.63 kg/day (8 lb/day) when operated at a current of 11.4 amperes. The maximum planned production was 4.54 kg/day (10 lb/day).

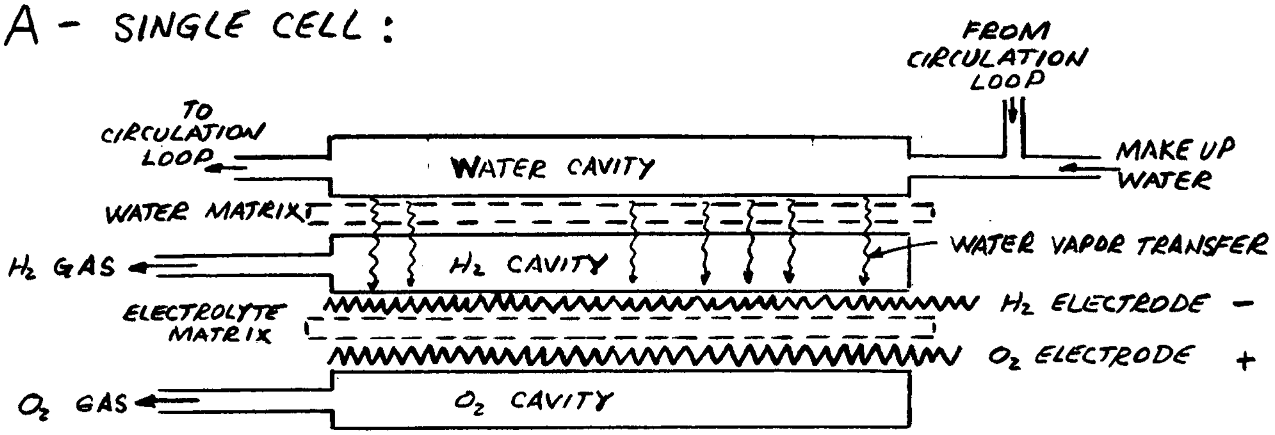


HEAVY LINES INDICATE FUNCTIONAL PATHS
DURING NORMAL AUTOMATIC OPERATION

FM	FLOWMETER	PI	PRESSURE GAGE
WTM	WET-TEST METER	PR	PRESSURE TRANSDUCER
S	SOLENOID	TI	TEMPERATURE GAGE
SW	SWITCH	TR	TEMPERATURE TRANSDUCER
FO	ORIFICE		

FIGURE 3-5 STATIC VAPOR FEED UNIT, MECHANICAL SCHEMATIC

A - SINGLE CELL:



B - TOTAL SYSTEM:

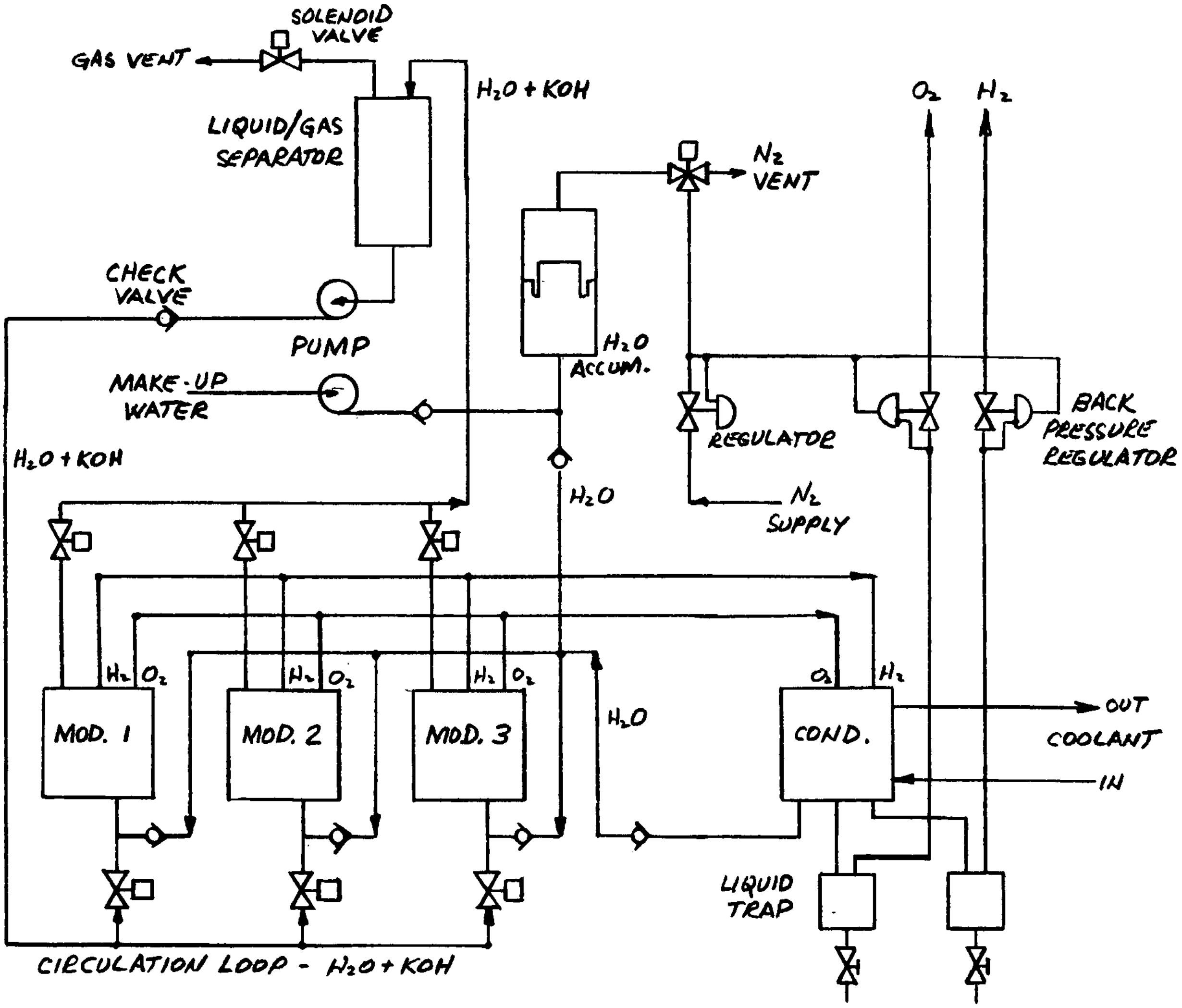


FIGURE 3-6 SVFU SIMPLIFIED MECHANICAL SCHEMATIC

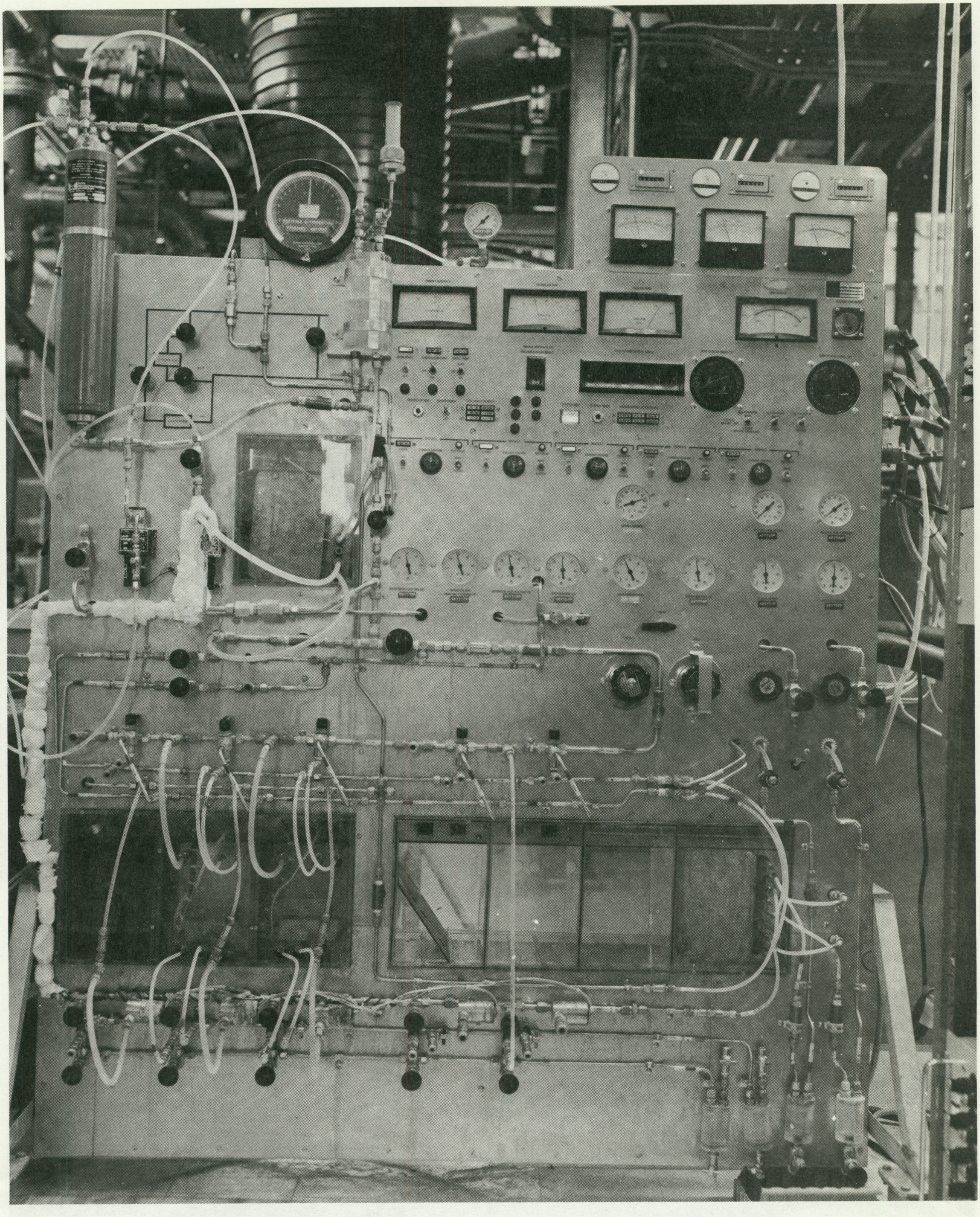


FIGURE 3-7 STATIC VAPOR FEED UNIT, FRONT VIEW

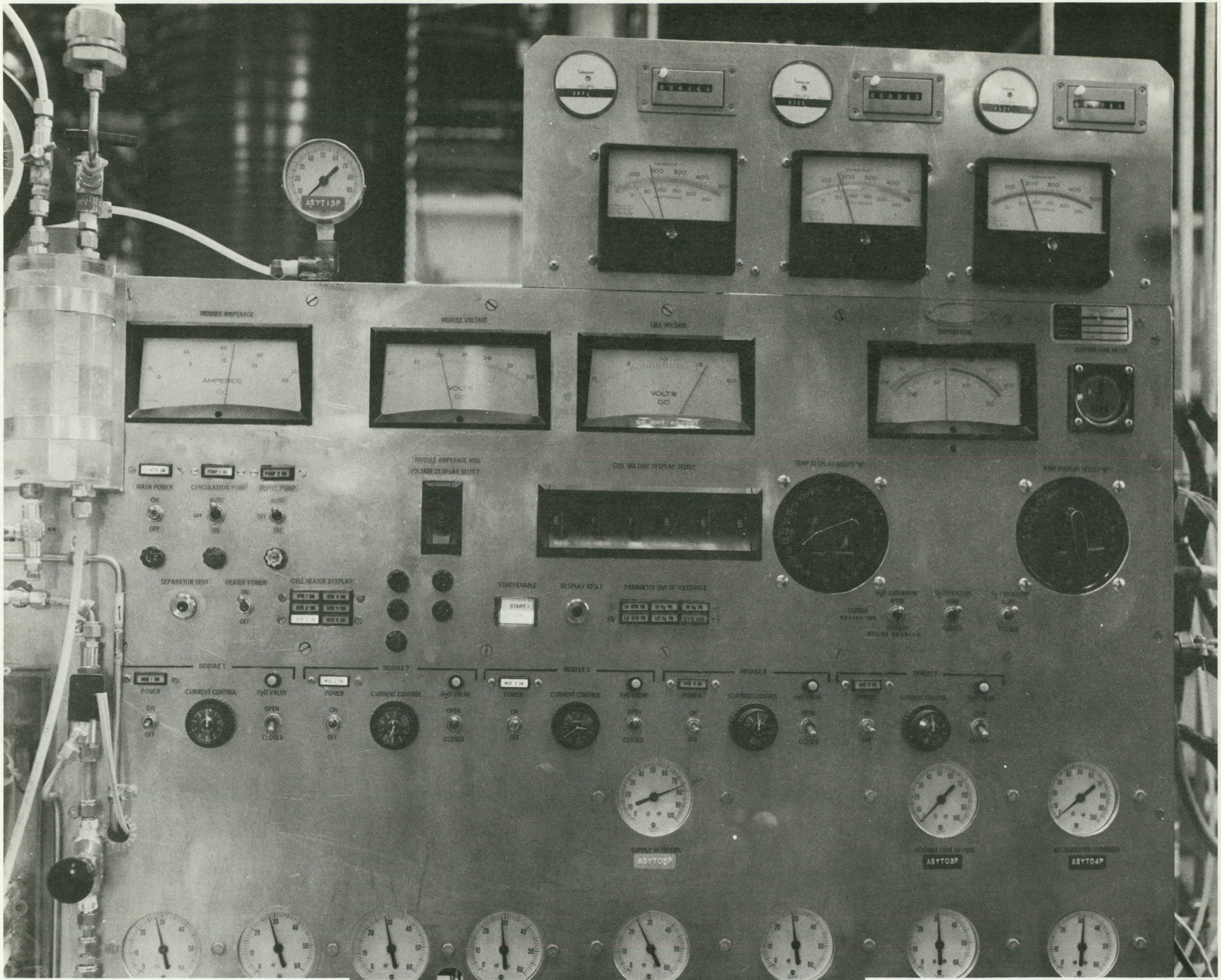


FIGURE 3-8 STATIC VAPOR FEED UNIT, FRONT PANEL

The nominal oxygen and hydrogen discharge conditions downstream of the condenser/separator were 31.0×10^4 N/m^2 (45 psia) at ambient temperature and a dewpoint of approximately 292°K (66°F).

Current to each electrolysis module was regulated by one of three methods, depending on the mode of operation selected. Normally, a current-control potentiometer fixed the current to the module. During analog control, the current was regulated by sensing the oxygen accumulator pressure downstream of the unit to adjust the production rate to meet system demands. Automatic current control for the orbital duty cycle was provided but not used. Current to each module was adjustable from 0 to 15 A (0 to 130.0 mA/cm^2) (0 to 121.0 A/ft^2) with the design operating point at 11.4 A (99.0 mA/cm^2) (92.0 A/ft^2).

3.2 Operating Configurations

Each system was to operate under slightly different conditions and have different data recorded. Mean O_2 production from each unit was to be 3.63 kg/day (8 lbs/day) for the first 13 weeks, the 15th week and final five weeks of the test. The 14th week of the test was to be devoted to demonstration of the capability to operate with an orbital duty cycle; a 90-minute orbit with a 50/40 day/night ratio was to be simulated. The O_2 production rate was to be 3.63 kg/day (8 lbs/day) in the day period and a minimum production rate commensurate with system design capability in the night period. At the end of the 15 weeks, the oxygen production rate was to be manually increased in 0.23 kg/day (0.5 lb/day) increments until the maximum design O_2 production rate of 4.54 kg/day (10 lbs/day) was reached; this operating level was to be maintained until the final five weeks of the test at which time the production rate was reduced to 3.63 kg/day (8 lbs/day).

3.2.1 Circulating Electrolyte Unit (CEU)

The circulating electrolyte unit contained four modules, each containing 16 cells in two banks of eight cells. Three of the four modules were to be cycled between a high current and low current modes to meet the required oxygen generation rates. The fourth module was to be on "standby" and operate continuously in the low current mode unless one of the other operating modules failed. Failure of one operating module would necessitate placing the standby module in full operation and changing the cycle frequency between high and low modes to meet the required oxygen generation rate. The circulating electrolyte unit was to be operated without accumulator control. A selector switch for continuous or cyclic operating mode and a digiswitch for high mode time on the two-gas controller signal simulator was adjustable to provide the desired operating mode and oxygen output rate.

3.2.2 Static Vapor Feed Unit (SVFU)

A modified vapor feed electrolysis unit with five modules of 15 cells each was to be provided for the 26-week test period. Three modules (design configuration) of the five were to be used in the 26-week Performance/Endurance test. Two of the three operating modules were to have the NASA/Langley Research Center improvements incorporated (1970 design). The remaining two modules (1968 design) were to be held on standby and not connected to the unit until required to replace any malfunctioning module. Removal and replacement of modules were to be accomplished manually. Oxygen generated by the three operating modules would flow directly into an accumulator. An outlet valve on the accumulator was to be adjustable to provide a flow range of 3.63 to 4.54 kg/day (8 to 10 lbs/day) at the system design operating pressure.

3.2.3 Operating Limits

All testing was to be conducted within the voltage, current, temperature and pressure operating limits recommended by the manufacturer. These limits do not correspond to the nominal design range but represent the maximum and minimum steady-state values that can be tolerated without failure. If limiting values occurred, current/pressure was to be backed off to a safe operating point.

The environmental temperature around the vapor feed unit was to be maintained over the narrow range normally experienced in an air-conditioned laboratory and the conditions were to be monitored closely by the automatic data monitoring system.

Water supplies for the two electrolysis units were to be five-gallon bottles of industrial distilled water. Daily measurements were to be taken to determine consumption rates. Special preparation of the distilled water was not to be performed. Any special preparation desired by a system manufacturer was to be incorporated in and be a part of that system.

3.3 Special Requirements

This section defines some of the major special requirements that were unique to the test program, and were followed closely during the execution of the systems testing.

3.3.1 Failure Analysis

In the event of failure, every effort was to be made to identify the cause of failure in sufficient detail to avoid any dangerous conditions, correct the problem and return the system to full operation as quickly as possible. After the system was restarted with approval by the test committee, a detailed analysis was to be performed to identify the mechanism of failure and determine how the problem could be eliminated in the future. Restarting as soon as possible after correcting a failure rather than after complete failure analysis was predicated on the desire to obtain maximum operating time during the course of the test program. A system failure was defined as any time the system was automatically or manually stopped because of an out-of-tolerance or impending out-of-tolerance condition. Parameters showing trends in a direction indicating potential failure would not be cause for shutdown unless the rate of change of the value was rapid and it was obvious the system would stop or fail within a few minutes. Failures occurring during the performance/endurance testing were to be reviewed by the test committee via telecon as soon as practicable after identification of the cause of failure and establishment of a course of action for repair. The test committee would approve all corrective action prior to its incorporation into the system.

3.3.2 Non-Interference Operation

Both electrolysis systems were to be operated with a "hands off" philosophy. That is, system operators were not to adjust valves or current control potentiometers, or make other adjustments to return the system to more nominal operating conditions. If it was evident from a review of the system data that a system would be damaged from continuous operation, the system could be stopped and corrective action taken as indicated in paragraph 3.2.1. All personnel associated with this test were responsible for ensuring that inadvertent actuations or unapproved deviations of test conditions did not occur. This provision did not preclude accomplishing any scheduled maintenance described in and required by MDAC-G3017, Operations and Familiarization Manual for Facility, Data Acquisition and Water Electrolysis System Test Support Equipment or MDC-G3018, Operations and Familiarization Manual for Static Vapor Feed Water Electrolysis Unit. (3, 4)

3.3.3 Data Management

Approximately 200 parameters of data from both electrolysis units were to be monitored on a continuous basis as long as the systems operated. Data would be recorded on magnetic tape at one-minute intervals. On-line printout of data would be at one-hour intervals, except for the last 10 to 15 minutes of system operation prior to failure when off-line printouts of the data would be obtained. Data would be printed at 10 minute intervals during the orbital simulation period and for 5-day periods during the 2nd, 12th and 24th weeks of the analog current control period. All data collected would be reviewed manually and pertinent data plotted manually to show the changes occurring within the system parameters as a function of operating time.

3.3.4 Test Readiness Reviews

Two test readiness reviews were to be held before testing could commence. The first meeting preceded the checkout testing. As part of the first meeting, the MDAC industrial safety representative was required to provide a statement signifying acceptance of the test equipment and instrumentation. The successful conclusion of this first meeting resulted in a certification of "Readiness for Test: Checkout Run." The second meeting was held after completion of the checkout testing. Successful completion of this second meeting resulted in certification of "Readiness for Test: Performance/Endurance." These certifications were constraints upon initiation of all testing.

This test committee was composed of the contractors involved and representatives from three NASA development centers, the Manned Spacecraft Center, the Langley Research Center and the Ames Research Center. The committee controlled the proceedings in order to achieve a high degree of objectivity of the results. The test committee's management philosophy was adapted to pool capabilities and to allow an interchange of ideas in the event that changes in operating conditions or hardware were required.

3.4 Test Parameters

3.4.1 Current Tests

Each operating vapor feed module position had its own current control potentiometer. Standby modules were to be kept ready for rapid installation into the system in the event of operating module failures. During analog control current levels were to be controlled by O_2 demand and were to correspond approximately to the operating lines of Figure 3-9. Average current was to be approximately 11.3 amperes per module at 3.63 kg/day (8 lbs/day) O_2 production and approximately 14.1 amperes per module at 4.54 kg/day (10 lbs/day) O_2 production as shown in Figure 3-10. Actual current values were to very up to $\pm$ 1.0 amperes from the average condition to test the automatic oxygen-generating rate control.

The circulating electrolysis unit was to be set to operate at 12 amperes in the high current mode and 4.6 amperes in the low current mode. The ratio of high mode to low mode operating time was to be approximately 62% to 38% at 3.63 kg/day (8 lbs/day) and 97% and 3% at 4.54 kg/day (10 lbs/day). The cycle frequency equipment was to be provided by the unit manufacturer. The cycle time in the continuous operating mode was to be approximately 100 minutes, with the high mode time adjustable in one-minute increments. The cycle time in the cyclic operating mode was to be 94 minutes, with 55 minutes on and 39 minutes off. During the "on" portion of the cyclic operating mode, the high mode time was to be adjustable in one-minute increments. During the "off" portion of the cycle, the electrolysis current was to be zero.

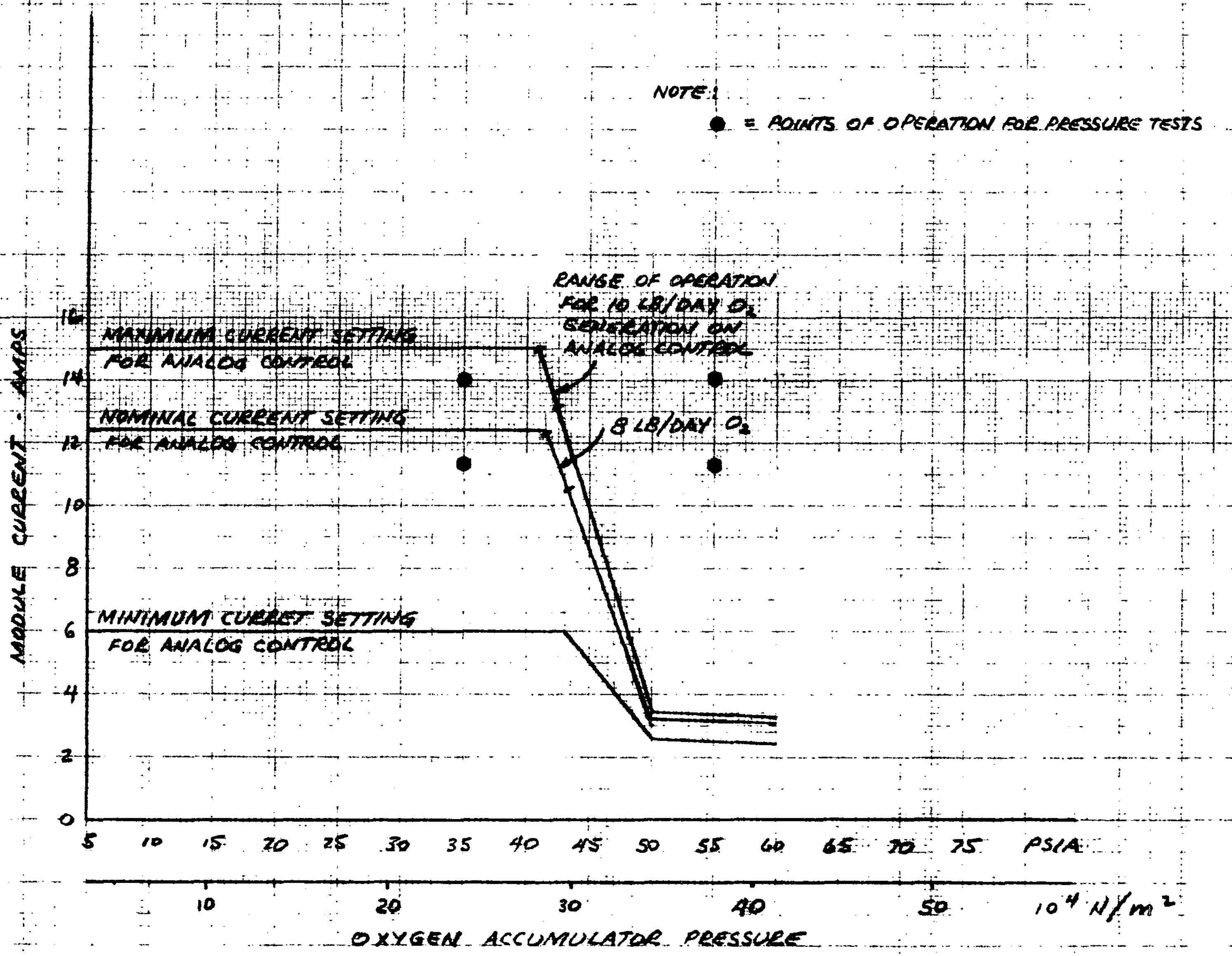


FIGURE 3-9 ACCUMULATOR PRESSURE - O_2 DEMAND RELATIONSHIP (SYEU)

POUNDS OF OXYGEN PER DAY $= \frac{N}{63.4} \left(\Sigma \eta I \right)$

WHERE:

N = NUMBER OF CELLS/STACK

I = CURRENT FOR EACH STACK

η = PERCENT OF TIME EACH STACK IS AT EACH CURRENT LEVEL

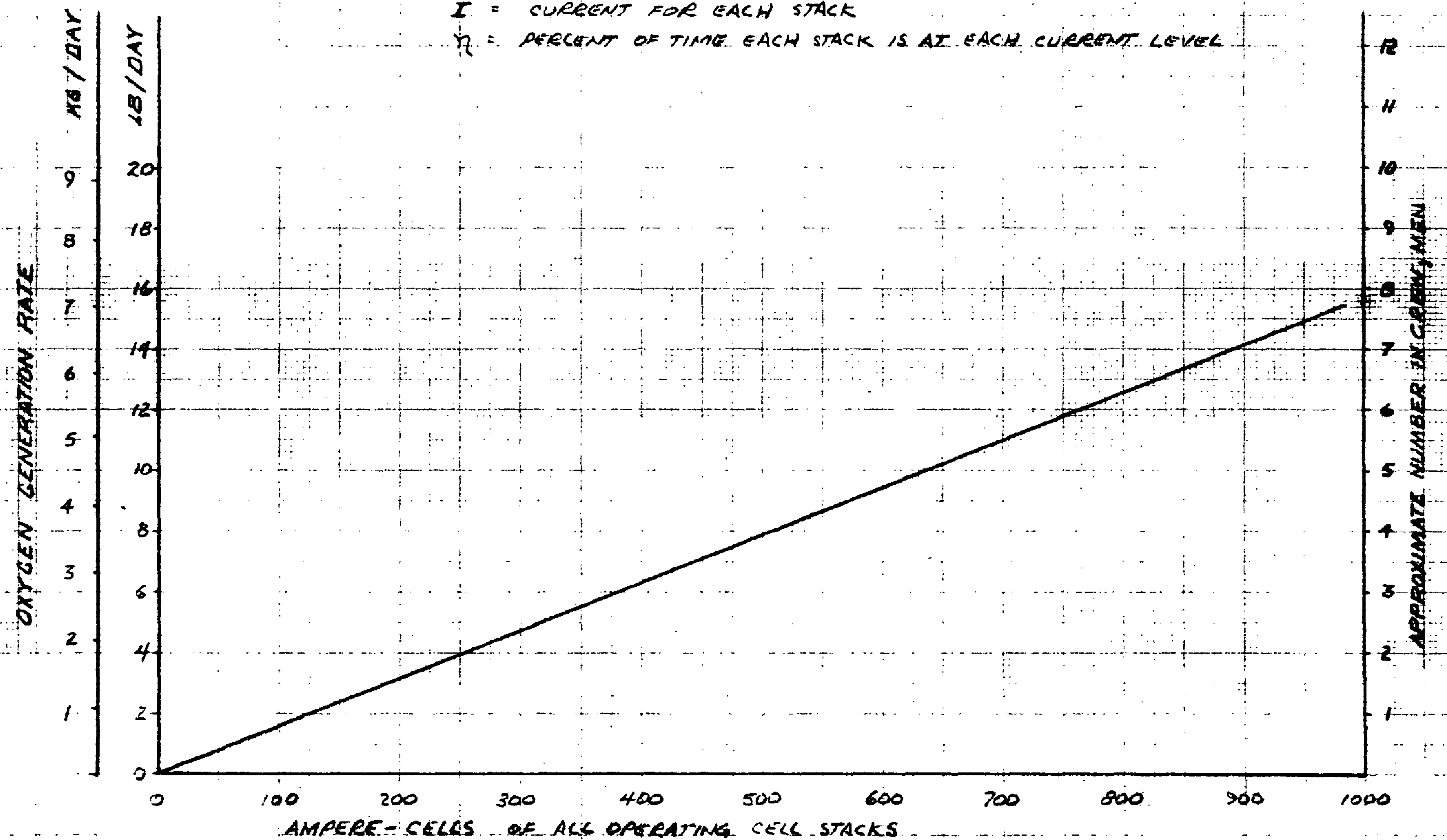


FIGURE 3-10 WATER ELECTROLYSIS SYSTEM OXYGEN GENERATION RATES

3.4.2 Pressure Tests

Three overall static vapor feed unit operating pressures were to be used at 3.63 kg/day (8 lb/day) O_2 production rate. These system pressures were a low of 24.1×10^4 N/m^2 (35 psia), a design or nominal pressure of 31.0×10^4 N/m^2 (45 psia), and a high pressure of 37.8×10^4 N/m^2 (55 psia). The SVFU current was to be controlled by the oxygen demand (O_2 accumulator pressure) in accordance with the operating line in Figure 3-9 in portions of the testing only at the design or nominal operating pressure. The majority of the tests were to be run at nominal pressure. The high and low pressure operating values were to be used three weeks each in order to evaluate the effect of pressure on performance. An accumulator was not to be used during high and low pressure operation; therefore, for these pressures operation would be fixed current levels of either 11.3 amperes per module or 14.1 amperes per module as shown by the black dots on Figure 3-9.

The circulating electrolyte unit H_2 and O_2 discharge pressures were to be at 1.03×10^4 N/m^2 gage (1.5 psig) throughout the test. The interface discharge plumbing was to have a maximum pressure drop of 1.03×10^4 N/m^2 gage (1.5 psig at an oxygen output rate of 4.72 kg/day (10.5 lb/day).

3.4.3 Accumulator Control Tests

Addition of an accumulator to the static vapor feed unit was to test the effectiveness of the automatic oxygen-generating rate control of the unit. The accumulator was to be preset with a controlled leak rate equal to the desired O_2 production. Oxygen generation rate was to be controlled by an error function generated by the accumulator pressure. Thus, when the discharge valve position was changed, flow into and out of the accumulator would not balance. The accumulator pressure changes would generate a signal for a change in O_2 production. The control characteristics of the unit was to correspond only to the design operating line in Figure 3-9. The accumulator would not be used during orbital simulation test period or during high and low pressure tests. Variations in current values during this test were to be up to ± 1.0 amperes per module from the average current levels identified for the test; that is, 11.3 amperes and 14.1 amperes.

The circulating electrolyte unit was not to be subjected to accumulator control tests as described above.

3.4.4 Orbital Simulation

During the 14th week of the program system operation was to be adjusted to simulate day/night effects of an orbiting station. The orbital duty cycle was to be approximately 90-minutes and have a day/night ratio of approximately 50/40. The production rate was to be approximately 3.63 kg/day (8 lbs/day) in the day period and approximately 0 to 0.91 kg/day (0 to 2 lbs/day) in the night period for an average of about 2.12 kg/day (4.67 lbs/day) during this test period.

The static vapor feed electrolysis unit was to operate at an average current of 11.3 amperes during the "on" period of the orbital simulation and at as low a current level as practicable during the "off" or dark period of the orbit. This low current level was necessary to maintain system pressures. An accumulator would not be used during orbital simulation tests.

The circulating electrolyte unit was to be operated with one 62% high mode and 38% low mode cycle accomplished in each "on" period of an orbit, and zero current to all modules during "off" period of an orbit.

3.4.5 Time-Line of Test Parameters

Table 3-1 shows the time-line of events to be followed in executing the performance/endurance test. All changes from one set of prescribed conditions to any other set were to be made in accordance with this schedule. Any deviations from this schedule were to be made only with approval of the test committee. All normal changes were to be made at noon on the date specified in the line labeled "Tuesday Date." If failures occurred which caused deviations from this schedule, every effort was to be made to get back on schedule as soon as possible.

3.5 Test Measurements

During the operation of each electrolysis system, a number of operating measurements were to be made and recorded. The measurements selected were identified as the ones most meaningful for evaluating the performance of the system during long-term operation. These measurements included:

Tuesday Date	26 Oct	2 Nov	9	16	23	30	7 Dec	14	21	28	4 Jan	11	18	25	1 Feb	8	15	22	29	7 Mar	14	21	28	4 Apr	11	18
Week of Test	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Oxygen Production, kg/day (pounds/day)	3.63 (8.0)													*	3.63 (8.0)	/	4.54 (10.0)					3.63 (8.0)				
Average Current (vf only) (amps per module)	11.3														11.3	/	14.1					11.3				
% High Mode Current (LMSC only)	62														62	/	97					62				
System Pressure Operating Line - Low, Design and High Pressure (Vapor feed only)	Design 20.6 x 10^4 N/m^2 gage (30 psig)						a High ++ **	b Design	c Low **	Design 20.6 x 10^4 N/m^2 gage (30 psig)								a High **	b Design	c Low **	b Design		a High **	b Design	c Low **	b Design

+ Pressure # Test period ends 1200 25 April 1972

a = 34.4 x 10^4 N/m^2 gage (50 psig) c = 6.89 x 10^4 N/m^2 gage (10 psig)

b = 20.6 x 10^4 N/m^2 gage (30 psig)

* Orbital Duty Cycle Simulation - Typical Section of 107 Total Orbits

Hour of Test	1		2		3		4	etc.
Orbital Period	Day (~55 Min.)		Night (~39 Min.)	Day		Night	Day	
Oxygen Production, kg/day (pounds/day)	3.63 (8.0)		~0.68 (~1-1/2)	3.63 (8.0)		~0.68 (~1-1/2)	3.63 (8.0)	
Vapor Feed Unit Average Current (amps per module)	11.3		~0.5	11.3		~0.5	11.3	
LMSC Unit - Current (amps) Modules 1, 2, 3	(~36 Min.) 12	(~19 Min.) 4.5	0	12	4.5	0	12	4.5
Module 4 Current (amps)	4.5		0	4.5		0	4.5	

** No accumulator, fixed point operation.

Table 3-1 PERFORMANCE/ENDURANCE TEST TIME-LINE

3.5.1 Circulating Electrolyte Unit

- 64 cell voltages - voltage of all electrolysis cells within the system.
- 8 module voltages - 2 voltage values in each module, one for each of the cell banks.
- 8 module amperages - 2 current values in each module, one for each of the cell banks. Automatic overcurrent shutoff of current to individual modules is provided by 20 ampere circuit breakers.
- 4 module electrolyte temperatures - too high a temperature will cause automatic system shutdown by protection devices within the unit.
- 2 system electrolyte temperatures - temperature variations in the electrolyte as it enters the modules and as it returns to the reservoir.
- 1 coldplate temperature - temperature variations in the coldplate as a function of time.
- 3 system pressures - oxygen, hydrogen and reservoir pressures.
- 1 system current - total current of the system.
- O_2 and H_2 production rates and quantities (wet test meters).
- On/off status - operational status of system. The computer was to view this signal as a bilevel indicator.
- High current mode/low current mode switching time - operational status of system. The computer was to view this signal as a bilevel indicator.

Other performance parameters that were to be calculated and/or indirectly measured to determine changes in system operation included:

- Water consumption rates and quantities.
- N_2 consumption.
- Coolant flow rates and temperature to the heat exchanger and coldplate.

3.5.2 Static Vapor Feed Electrolysis Unit

- 45 cell voltages - with automatic shutoff by computer of any module containing a cell with a voltage in excess of 1.75 or 1.80 volts. Shutdown on value preset in computer memory and which could be set for each cell.

- 3 module voltages - a measure of the total voltage to a module with automatic shutoff by computer of any module with a total voltage exceeding 25.5 volts.

- 3 module currents - the total current to each module and used for calculating the gas production rate for each module and for the total system.
- 12 cell temperatures - 4 temperature pickups in each of the 3 modules with automatic shutoff by computer of any module with a thermocouple exceeding 369°K (205°F).
- 11 system pressures - all fluids in the system at various places.
- 1 differential pressure - pressure differential across circulating loop manifold to determine any degradation as a function of time.
- 14 system temperatures - all fluids in the system at various places.
- 3 liquid flow rates - to measure the signature changes as a function of time.
- 1 total system voltage - a measure of total voltage to the electrolysis system.
- 1 total system current - a measure of total current to the electrolysis system.
- O_2 and H_2 production rates and quantities (wet test meters).
- Ambient temperature - temperature of atmosphere surrounding electrolysis units.
- On/off status - operational status of system. The computer was to view this signal as a bilevel indicator.
- Chassis electrical potential to earth ground.

Other performance parameters that were to be calculated and/or indirectly measured to determine changes in the system operation included:

- Water consumption rates and quantities.
- N_2 consumption.
- Electrolyte circulation rate and frequency of pump operation for gas separation.
- Coolant flow rates to the condenser and coldplate.
- Frequency of dumping gas from the two-phase separator as well as quantity of gas dumped.

3.5.3 Chemical Analysis

During the test, special measurements were to be made to determine the extent of potassium hydroxide carryover from the electrolysis system by monitoring the pH change of water in bubblers downstream of the electrolysis units. This was to be done for both systems. The schedule was to be once weekly for the first month, then once every four weeks thereafter until the end of the test, a total of nine tests. Concentration of the electrolyte in the SVF unit was to be measured weekly by withdrawing a 1×10^{-5} m^3 (10 ml) sample and after proper dilution, titrating with a 1.0 normal hydrochloric acid solution. Whenever a quantity of electrolyte was withdrawn from the system, an equal quantity was to be added to the electrolyte loop to maintain constant concentration within the loop. Electrolyte concentration tests were to be performed weekly for the first month, then once every four weeks thereafter until the end of the test, a total of nine tests. Details of chemical analysis tests are described in Reference 3.

Output gases (H_2 and O_2) from each of the electrolysis units were to be tested for impurities by use of a Perkin-Elmer Model 154-D spectrometer. These tests were to be conducted on both electrolysis units in accordance with the following schedule: 2 samples first day; 1 sample each on day 2, 3, 5, 8, 15; 1 sample each at two-week intervals for remainder of 26-week test period. This amounts to a total of 19 samples for the 26-week test period. Organic contaminants in the electrolysis system discharge lines were to be analyzed by the use of a Perkin-Elmer Model 800 gas chromatograph. Details of gas analysis procedures are described in Reference 3.

3.6 Test Stand Configuration

Figure 3-11 shows the test stand configuration to be used in this test program. The figure shows, in block diagram format, the data management system, the electrolysis units, the laboratory facilities used to support the test and the interfaces existing between major assemblies. The test stand was designed for testing both the SVFU and the CEU. Water supplies for consumption by the two units were to be 0.019 m^3 (five-gallon) bottles of industrial distilled water. Twenty-eight volt direct current and 115 volt alternating current

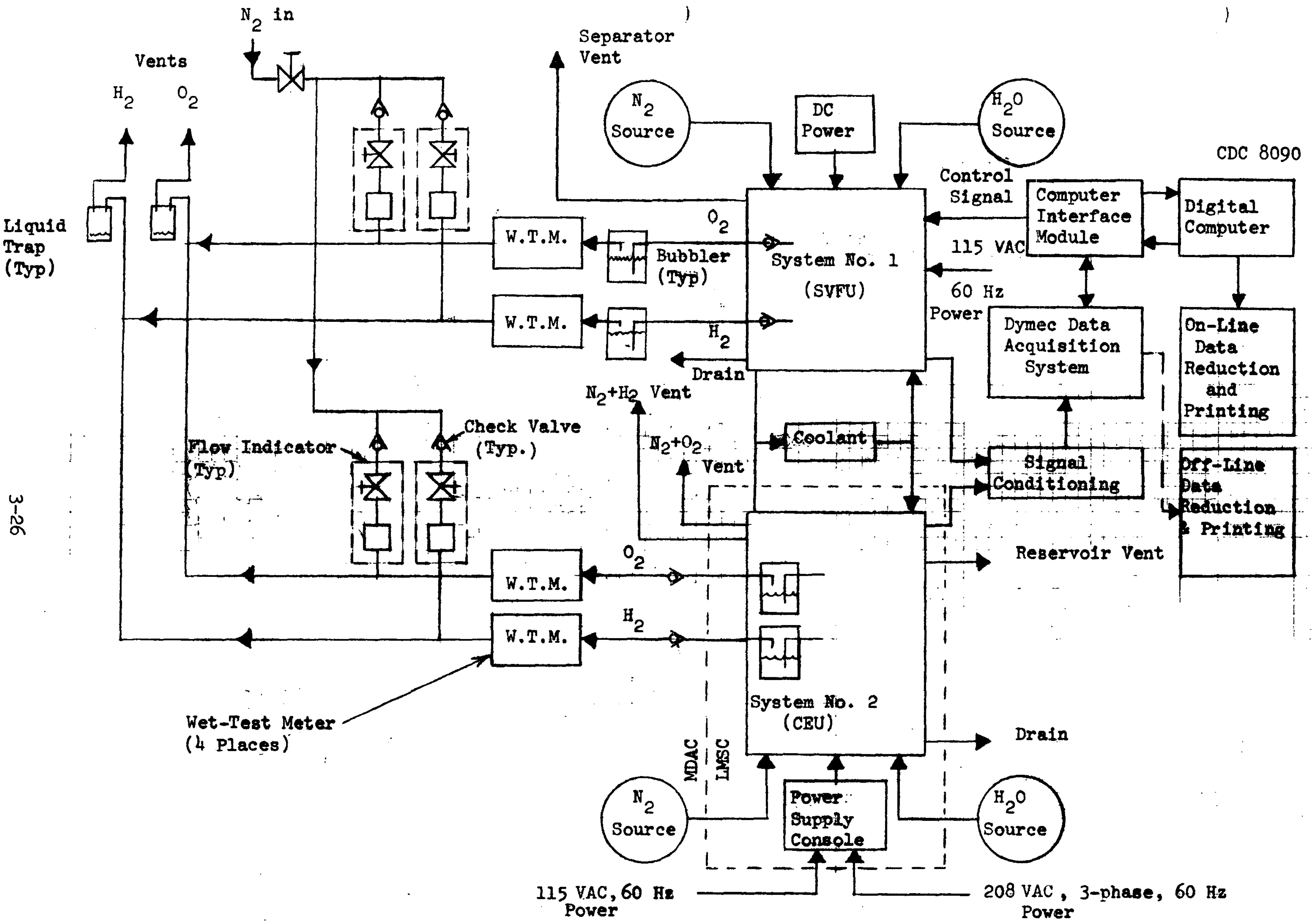


FIGURE 3-11 WATER ELECTROLYSIS SYSTEMS TEST FACILITY CONFIGURATION

were to be supplied to both units. In addition, the CEU would also be supplied with 208 volt alternating current. Figure 3-12 shows the left portion of the test stand which contains the wet test meters for the SVFU, the SVFU 28-vdc power supply, the oxygen accumulator and the separate flush cart for establishing initial electrolyte concentrations in the matrices of the SVFU modules. Figure 3-13 shows the right portion of the test stand which contains the wet test meters for the CEU, the CEU and the power supply console for the CEU. Figure 3-14 shows the signal conditioning console used to precondition all channels requiring conditioning prior to the signals being delivered to the data acquisition system.

The cooling necessary for the electrolysis units was to be provided from the MDAC Uniplant cooling system. Water in adequate quantities of approximately 6.3×10^{-4} m^3/sec (10 gallons per minute) at about 280°K (45°F) would be available. Each electrolysis unit was to be equipped with a flow meter to measure separate flow to the unit. This was a closed-loop circulating system. Due to the low pressure capability of the circulating electrolyte unit heat exchanger, an intermediate low pressure heat exchanger was provided.

Hydrogen and oxygen discharge gases were to be metered by wet test meters to enable operating personnel to cross-check the gas production rates against power used and water consumed.

The automatic monitoring and safe-control system block diagram is also shown in Figure 3-11. All signals generated by the two water electrolysis systems (about 200 channels of data) were to be signal-conditioned and sent to the Dymec Data Acquisition System. The control data into the data acquisition system was recorded by the system and simultaneously delivered through the computer interface module to the computer for comparison of each data signal with a preset value in memory. The data system is shown in Figures 3-15 through 3-17. Figure 3-15 shows the Dymec data unit with the Kennedy magnetic tape recorder and the interface unit. Figure 3-16 shows the front panel of the CDC 8090 computer where raw data was limit-checked and converted to engineering units. Figure 3-17 shows the CDC 1612 on-line printer used for periodic printout of all data.

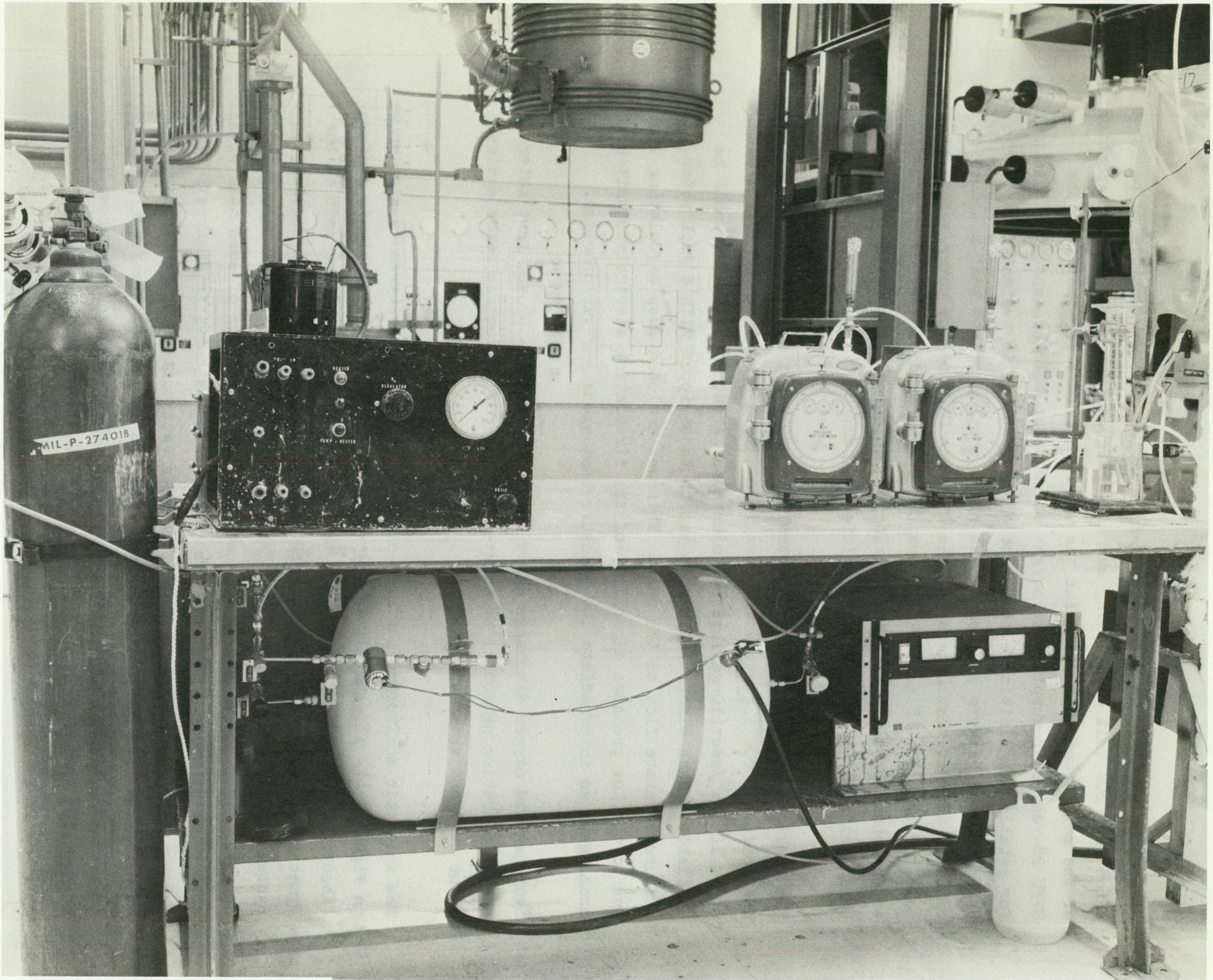


FIGURE 3-12 LEFT PORTION OF TEST FACILITY AREA

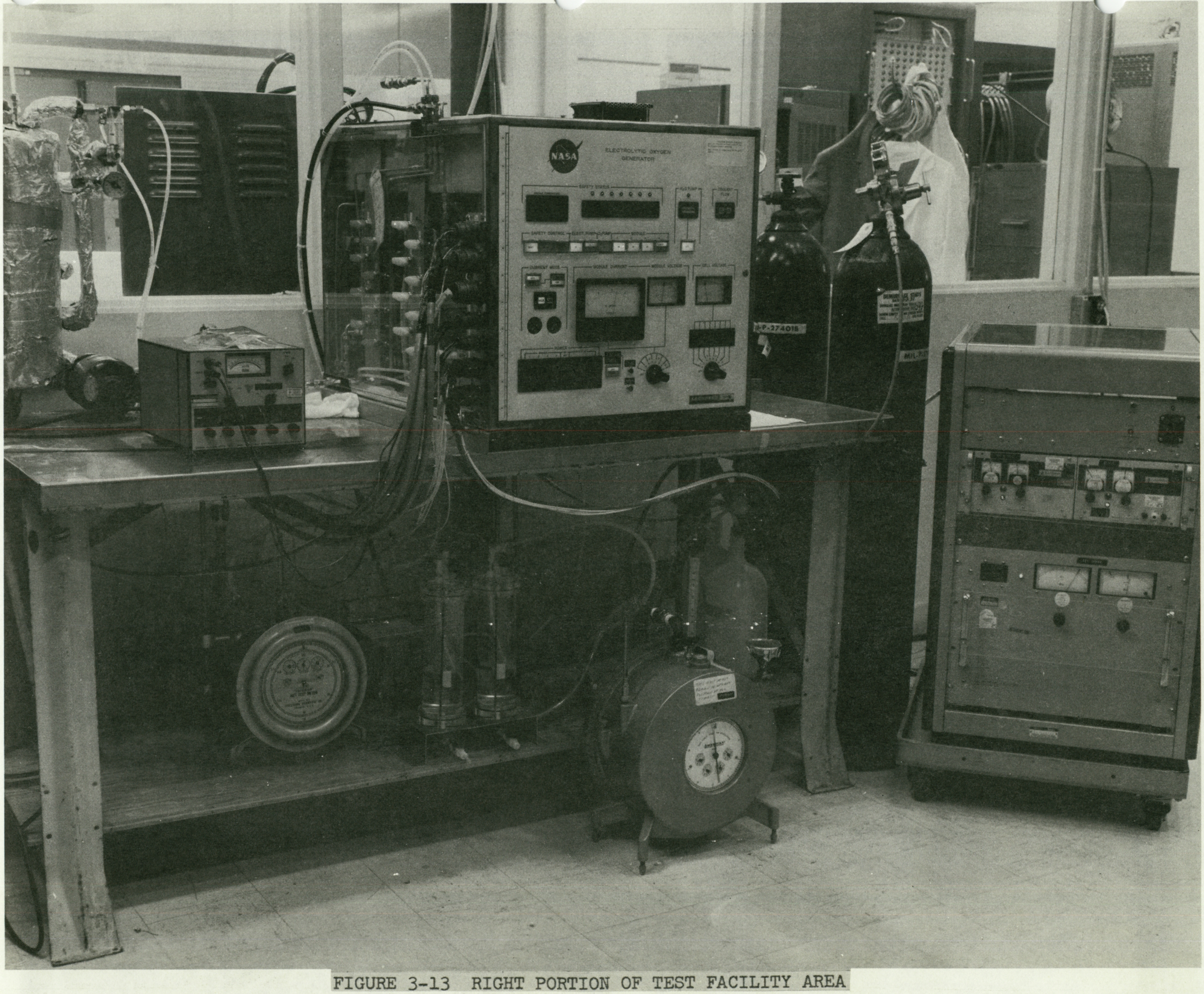


FIGURE 3-13 RIGHT PORTION OF TEST FACILITY AREA

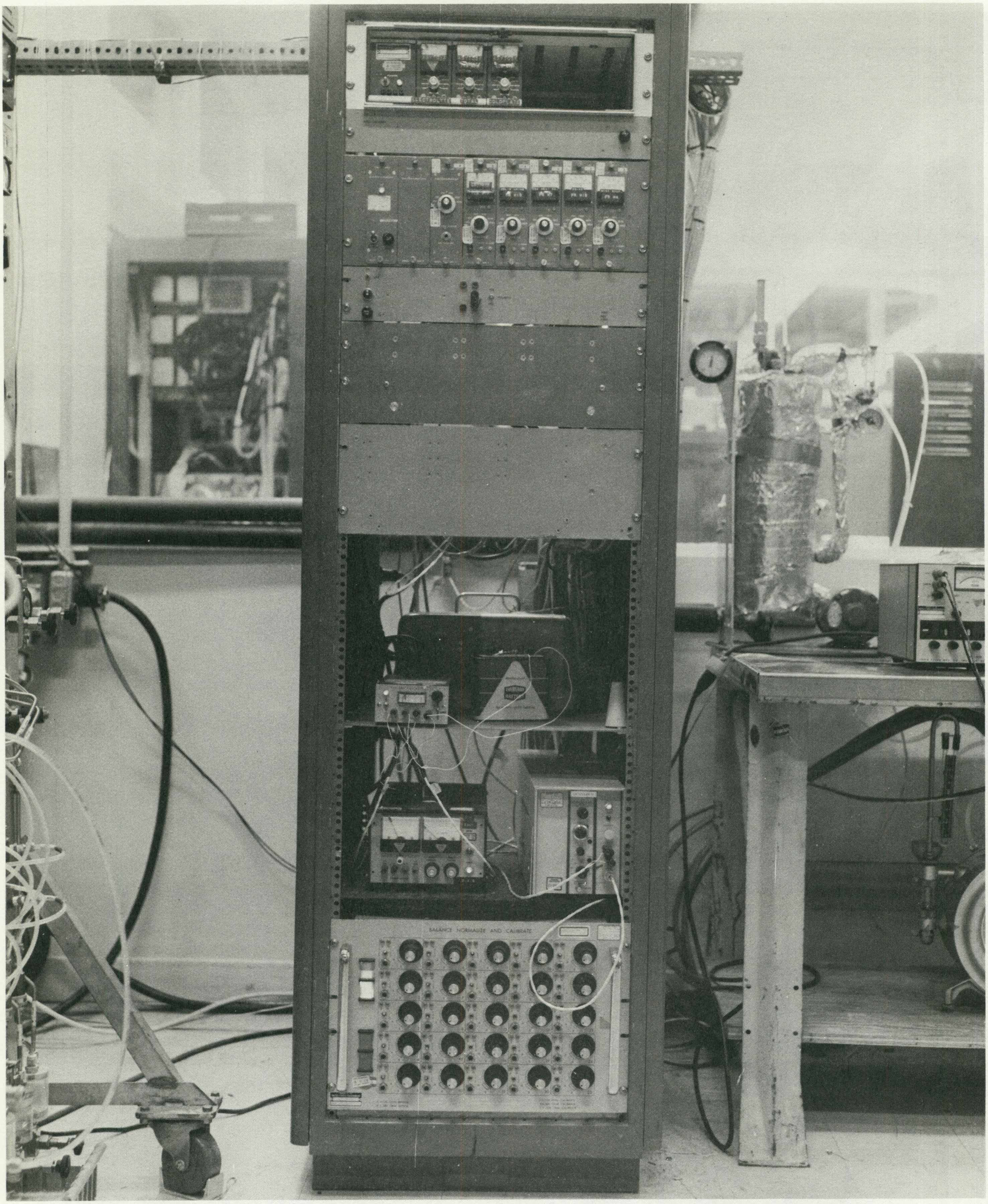


FIGURE 3-14 SIGNAL CONDITIONING CONSOLE, CENTER PORTION

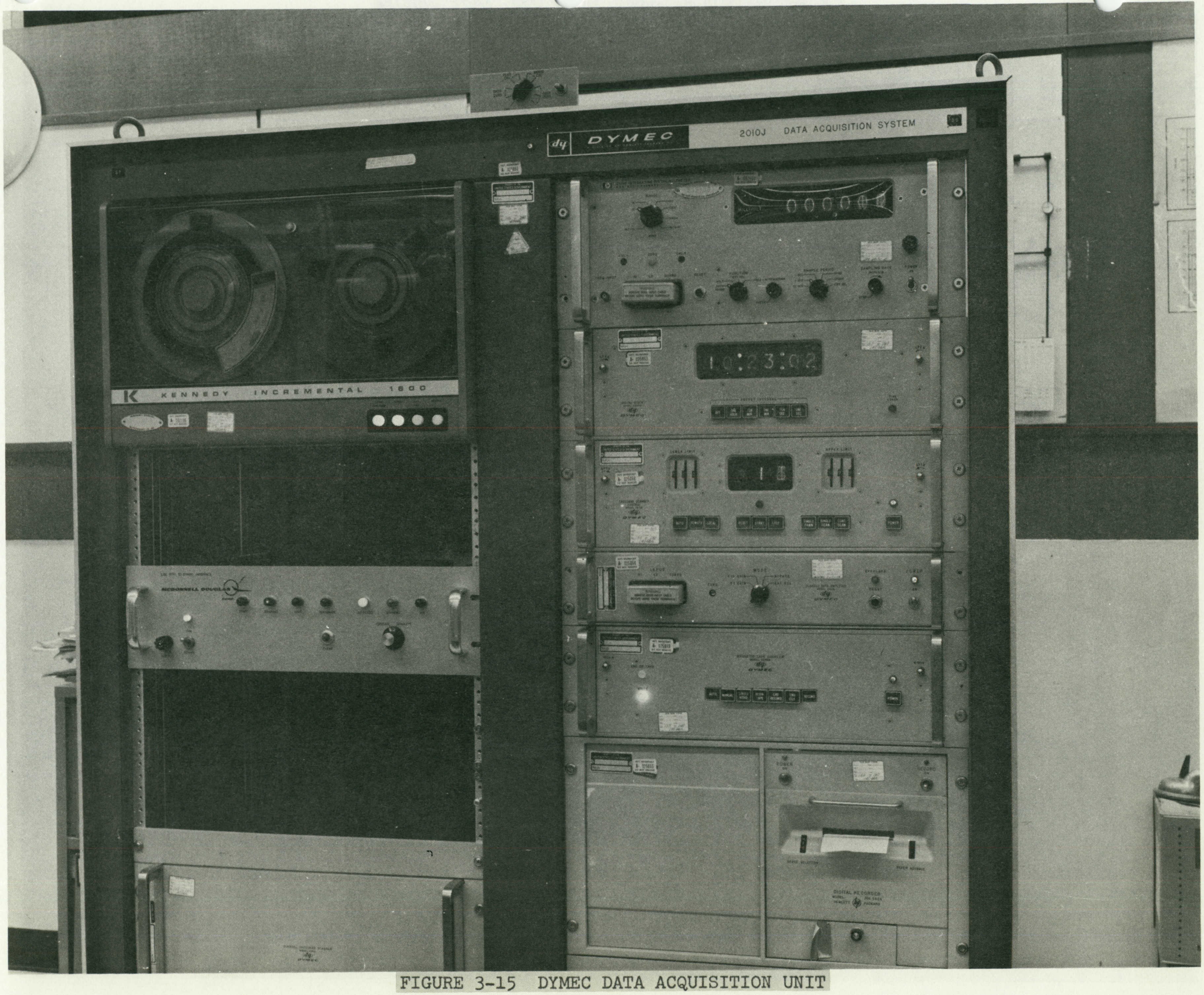


FIGURE 3-15 DYMEC DATA ACQUISITION UNIT

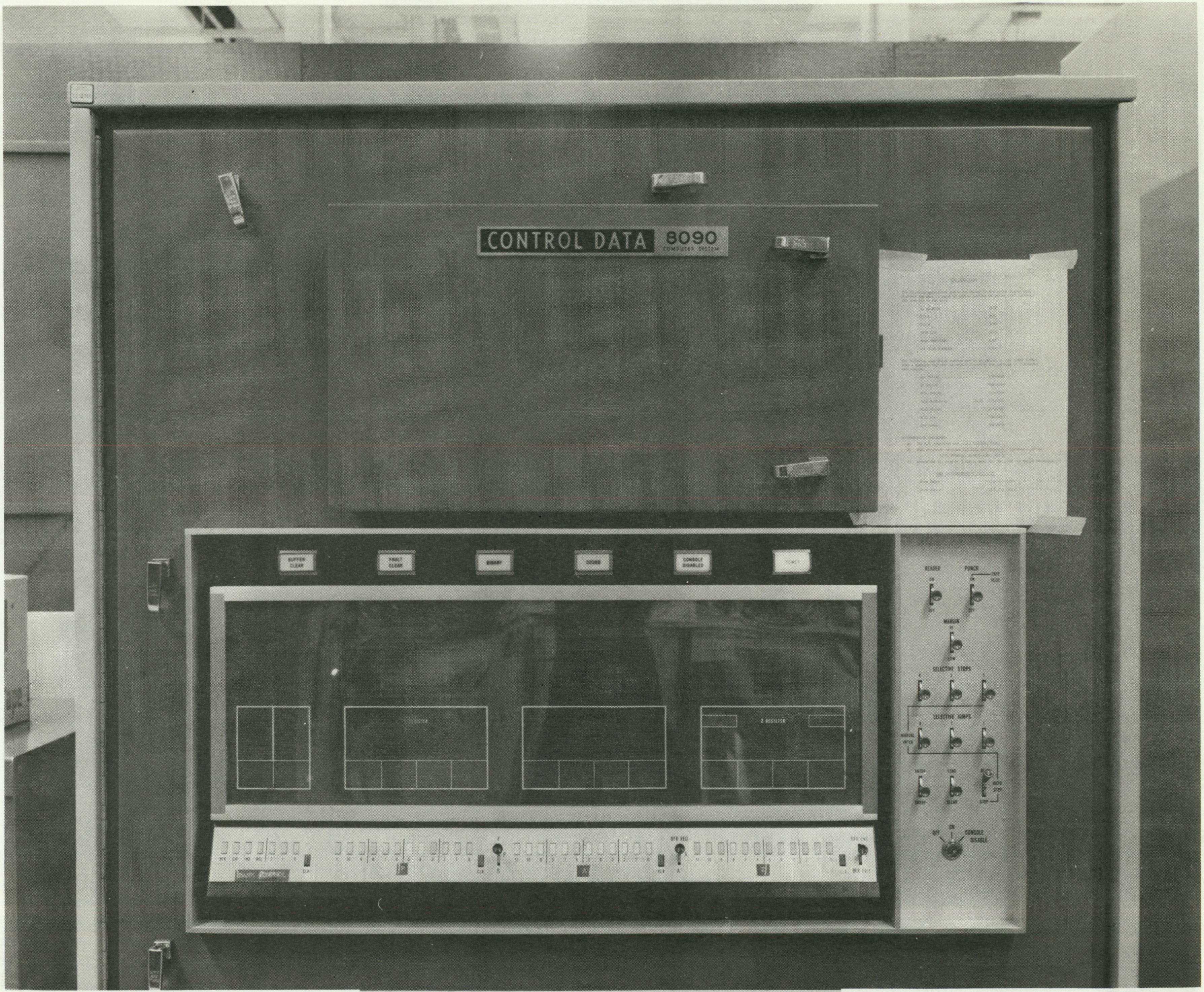


FIGURE 3-16 CDC 8090 COMPUTER CONTROL PANEL

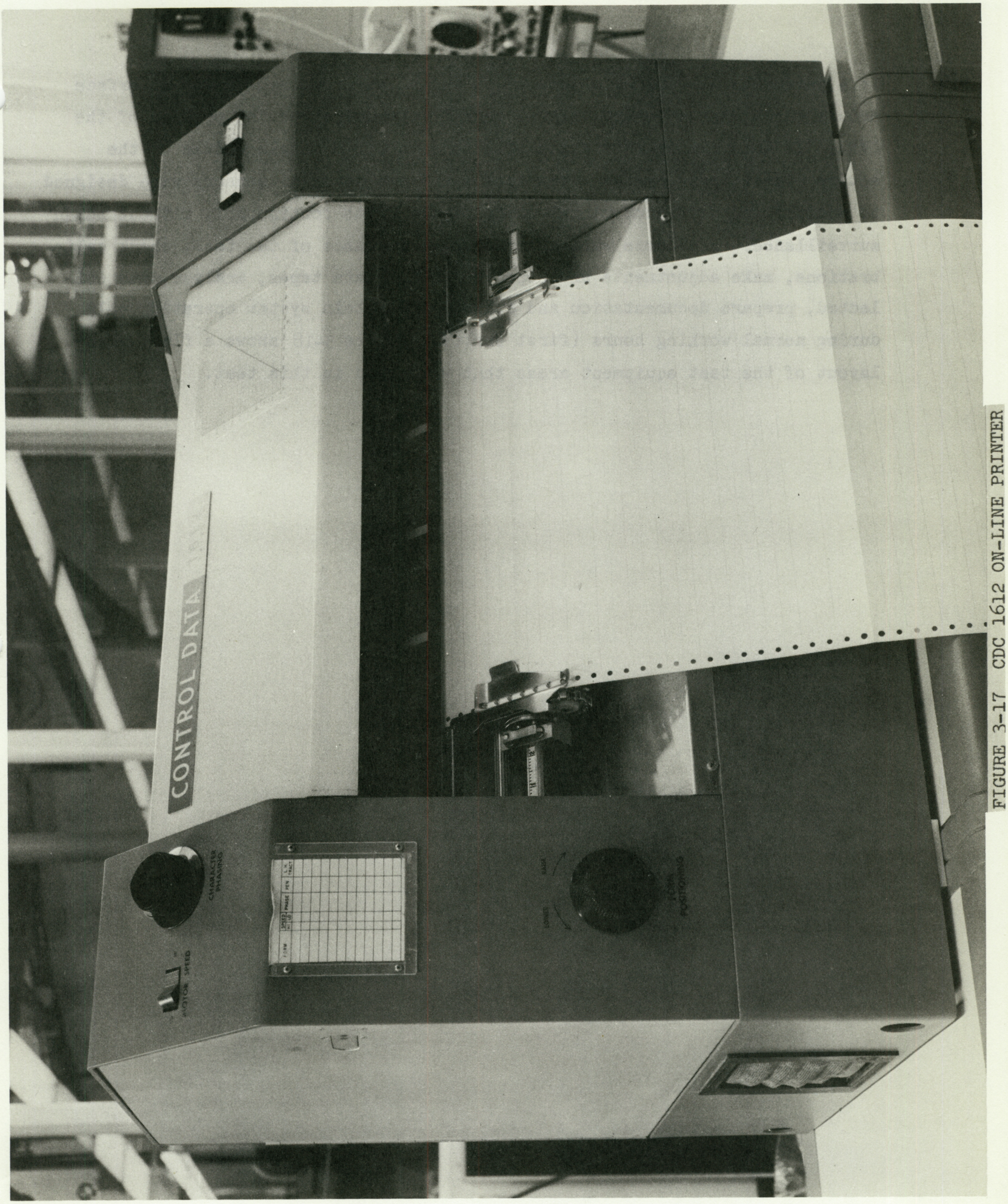
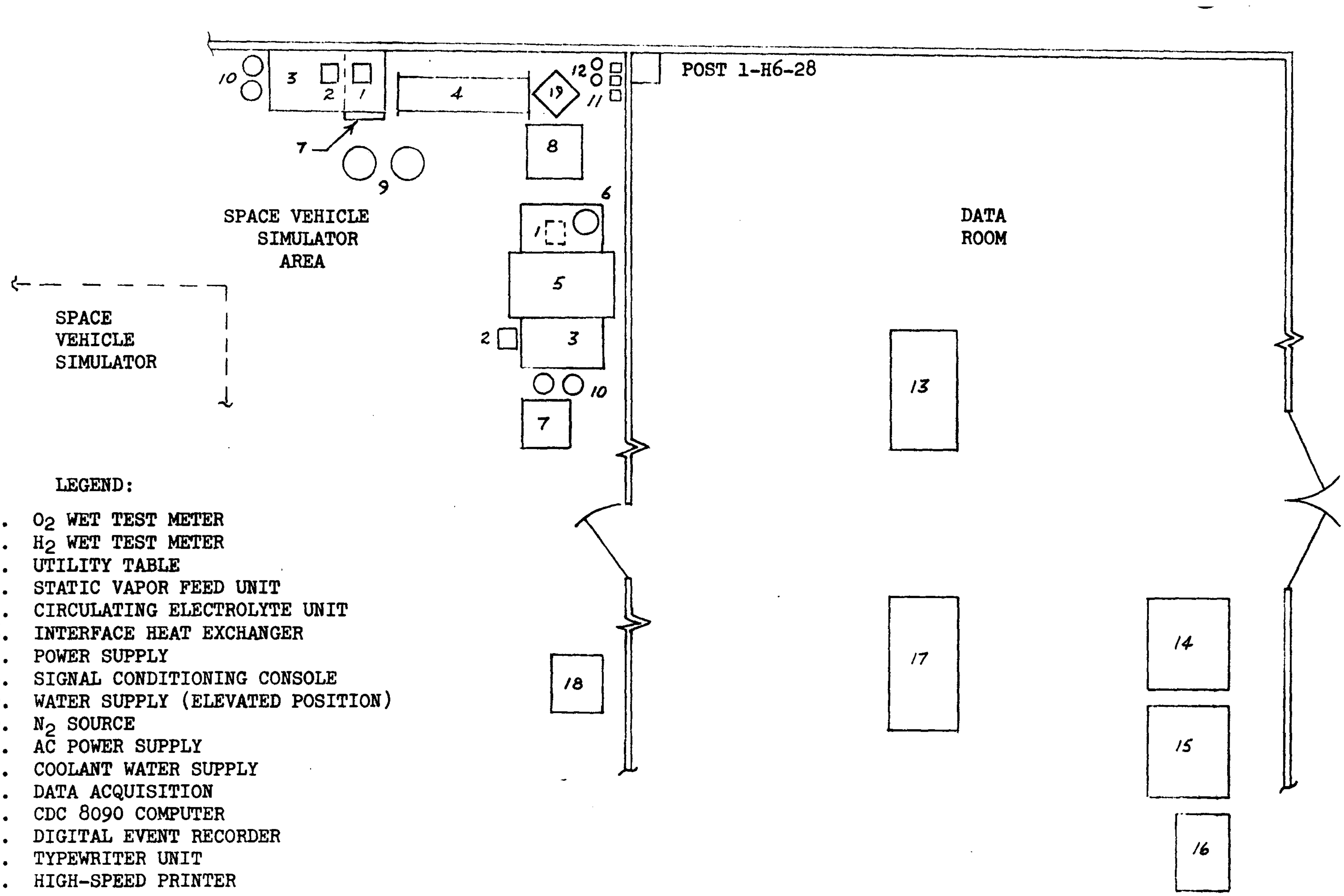


FIGURE 3-17 CDC 1612 ON-LINE PRINTER

If a parameter was out of tolerance, a signal was returned to the interface module which sent a control signal back to the malperforming portion of the SVFU. In this manner it was possible to shut off a single module or the entire electrolysis system. The test stand and integral sensors were designed to monitor and safe-control the electrolysis units continuously without human surveillance. Engineers were to observe performance of the test, check calibrations, make adjustments and repairs, change data tapes, analyze data collected, prepare documentation and otherwise maintain system operation only during normal working hours (first shift). Figure 3-18 shows a floor plan layout of the test equipment areas that were used in this test.



LEGEND:

1. O_2 WET TEST METER
2. H_2 WET TEST METER
3. UTILITY TABLE
4. STATIC VAPOR FEED UNIT
5. CIRCULATING ELECTROLYTE UNIT
6. INTERFACE HEAT EXCHANGER
7. POWER SUPPLY
8. SIGNAL CONDITIONING CONSOLE
9. WATER SUPPLY (ELEVATED POSITION)
10. N_2 SOURCE
11. AC POWER SUPPLY
12. COOLANT WATER SUPPLY
13. DATA ACQUISITION
14. CDC 8090 COMPUTER
15. DIGITAL EVENT RECORDER
16. TYPEWRITER UNIT
17. HIGH-SPEED PRINTER
18. BACK-UP POWER SUPPLY
19. PRESSURE GAGE PANEL

FIGURE 3-18. TEST EQUIPMENT AREA LAYOUT

4.0 CIRCULATION ELECTROLYTE UNIT TEST RESULTS

This section presents material on the test results obtained while operating the circulating electrolyte unit. The data is presented in narrative format from the receipt of the CEU, through the 80-hour checkout test and finally, through the 26-weeks of system testing. Some of the presented data have been summarized for clarity and continuity of presentation. Additional information and more detailed analysis on the performance of the CEU may be found in the LMSC report covering the same period of performance, Reference 5.

4.1 Unit Integration

The CEU was delivered to MDAC early in October 1971 and inspected for damage by the LMSC resident engineer. The unit was installed in the designated place in the test stand and all electrical, plumbing and mechanical interface connections made in accordance with interface document, Reference 6. Interface problems were not encountered in connecting up the unit. Next the unit was checked out and then started to determine if any operating problems existed. Only one problem pertaining to the CEU became evident. Electrical noise in the instrumentation was found to be originating within the CEU. This problem was not sufficient to cause delay in checking out the unit and it was expected that additional information relative to a solution would be obtained by continuing the testing.

After the initial checkout and after the first test readiness meeting, authorization was obtained to proceeed with the 80-hour checkout of the unit.

4.2 80-Hour Checkout Test

The CEU operated very well during all phases of the 80-hour checkout test. Operation was smooth and without any mishaps to cause shutdown of the system. Review of the data indicated that total and module current readings had to be read at the unit rather than by the Dymec data collection unit due to excess electrical noise on these lines. The noise was beyond the acceptable level of the Dymec and the information printed out was erroneous. Filtering was added to bring the module current into an acceptable range for the Dymec. Difficulty was still encountered and it was decided to operate the unit with module currents being provided to and recorded by the data acquisition system but not the total system current. Total system current would be obtained by reading the front panel meter on the unit. A difference was observed between the CEU current readings and the computer data. A digital voltmeter was added across the CEU ammeter to enable the LMSC resident engineer to calculate the error so that a scale factor could be applied to the computer data during the 182-day test. A very slow leak of electrolyte developed in the heat exchanger at a reducer bushing. This was sealed by cleaning the end plates of the leak and applying a liberal coat of epoxy on the entire area. The system never went to low mode when the timer was set at 97 to 100 minutes. The planned operation called for 97 minutes high mode operation and 3 minutes low mode operation when producing 4.54 Kg (10 pounds) of oxygen per day. Electrical resistance was added to the solid state timers to obtain more accurate operation. The solenoid valve controlling flow to the heat exchanger was observed to be chattering. This was eliminated by increasing the hysteresis of the signal actuating the solenoid valve.

4.3 Performance/Endurance Testing

The following paragraphs describe the overall performance of the circulating electrolyte unit during the 26 weeks of testing. Following the descriptive material is a section containing all the performance curves developed to show trends in performance of the unit. Next are a few short sections describing special evaluations that were performed on the unit.

4.3.1 Overall Unit Performance

Just prior to the start of the 26-weeks of testing on October 26, 1971, a final adjustment was made to the current levels of each cell bank. The adjustment was made to 12 amperes for the high mode and 4.5 amperes for low mode operation. All the modules remained essentially constant except for module 4B. This current level slowly drifted to the range of 6.2 to 6.5 amperes, depending on what operating mode the system was in at the time. The drift seemed to have stopped at that point.

On 8 November, the first unscheduled system shutdown occurred. Display indication was low system pressure. Some bubbles were observed in the fluid lines. An attempt was made to find out if gas was building up in a pump. The resident engineer switched back and forth between the pumps. Gas buildup did not seem to be a problem. On 11 November the system was shutdown due to high oxygen pressure. All plumbing external to the unit was checked for obstructions but no cause of shutdown could be found. At that time a pressure gauge, pressure transducer and strip-chart recorder were added to the system to monitor oxygen system pressure. While in manual mode the operator switched back and forth between high and low mode to see if there was any problem in the pressure or pump system. Problems were not evident. Also on this date an electrolyte leak was observed at the discharge fitting of the flowmeter for module number 1. The fitting was found to be broken thus necessitating complete shutdown of the system and draining of electrolyte. At the time the new fitting was installed, new O_2 and H_2 solenoid valves were installed as the old ones had, at an earlier date, demonstrated a tendency to stick. After completing all repairs and recharging the system it was operated until 13 November when automatic shutdown occurred due to low system pressure. In checking over the available printed data it was found that module 4 had restarted automatically three times during the period the system was shutdown. The system was then put in a safe shutdown mode for the remainder of the weekend.

On 15 November the system was operated for 7 hours and then shutdown overnight per the request of the NASA Program Manager pending further analysis of available data. On 16 November the system was restarted and operated normally for about one hour when it was discovered that module 4 current was reading as if the module were in high mode rather than standby as it should have been. The system was then shutdown and the integrated circuit chips associated with module 4 were replaced with spares. Close visual observation was practiced for a few days but significant changes in system performance did not occur. Until the problem could be properly resolved and as a safety precaution module 4 was to be turned off each night and over the weekend periods. This procedure was followed for the balance of the 26-week period. The cause of the earlier malfunction was never identified, nor did it recur.

On 1 December the system shutdown leaving an indication of low system pressure. Integrated circuits on cards W2 and W3 were replaced. Also the shroud on the electrolyte reservoir was loosened to visually determine if air was being trapped in the reservoir and subsequently being pulled into the pump inlet line. Nitrogen was intentionally supplied to the pump inlet line to see what quantity of gas was required to cause shutdowns. It took a much larger amount of nitrogen gas to cause a shutdown than had ever been observed in the system. Therefore, it appeared that gas entrapment was not causing the unexplained low pressure shutdowns. The limits on the low system pressure shutdown were reduced from 8.96×10^3 to 7.93×10^3 N/m^2 gage (1.3 to 1.15 psig) to increase the band between normal system operation and the shutdown pressure. Prior to restarting, both circulating pumps were purged to remove all trapped gas. On 3 December the system was again shutdown due to low system pressure. Four new test points and a filter network were added to integrated circuit cards W1 and W2 and a strip chart recorder attached. This was done to help identify the source of the stray shutdown signals. The pressure transducers signal circuitry was also modified so that if low system pressure actually occurred, the strip chart would indicate the problem. If a stray signal were causing the shutdown the trace would not indicate a shutdown.

On 11 December the system shutdown with an indication of high oxygen partial pressure. The unit remained shutdown the rest of the weekend. The pressure transducer signal was brought out to the recorder.

On 14 December the unit was shutdown by the resident engineer because it was observed that the gas being generated by the unit was not being discharged through the water bubblers. Detailed inspection indicated that at 1702 the previous evening a stray signal deactivated the gas discharge solenoid valves. This resulted in the oxygen and hydrogen mixing and discharging out the normal nitrogen vent. This produced a very hazardous situation. Two changes were made, one to eliminate the hazardous situation and the other to assist in determining the source of the stray signal. The original vent line was separated into two lines, the original vent line being used for oxygen and a new vent line being used for hydrogen and discharging the hydrogen outside the laboratory building. The cause of the problem was thought to have been a power failure, long enough for the solenoids to drop but not long enough for the system to shutdown. For this reason, signals from the power supplies were added to the recorder to see if there was ever a temporary drop in power to any circuit of the equipment. The 8-channel recorder was now monitoring 5 pressure signals and the 30v, 24v and 5v power supplies.

A change was made to the configuration of module 4 for the nightly and weekend shutdowns to help in diagnosing the problem. The coaxial cables were disconnected and the circuit breaker and switch left on (in standby mode) so that if there was a failure and the system shutdown it would be possible to observe any attempts to restart. This arrangement ensured a non-hazardous condition would exist for both personnel and equipment.

The unit was restarted on 15 December 1971 and operated continuously on modules 1, 2 and 3 without interference until 22 January 1972. This was a period of 38 days. Module 4 was operated daily from 0800 to 1700 during that period of time, but continued to be shutdown at night and on weekends as a safety precaution. On 22 January the electrolyte discharge fitting on module 4 broke and allowed system pressure to drop causing a system shutdown. Some KOH solution was also pumped out and ran down on circulation pump #2 causing a short in the 115 volt circuit. The short caused the facility circuit breaker to open, this in turn, shutdown the signal conditioning console. When the signal conditioning temperature reference junction box began to cool the computer received false information which it read as over-temperature conditions in modules 2 and 3 of the SVFU, this resulted in the SVFU also being shutdown. After the fitting on module #4 of the CEU was replaced and a new pump motor installed, the system was recharged and restarted. After restarting, it was noted that the module #3 temperature warning light would come on occasionally when the unit was in high mode. Pump #1, installed beneath module 3, was also running quite warm and it was throught that this heat was affecting the module temperature probe. The system was shutdown again and pump motor #2 was removed and the pump motor from #1 was installed in the #2 position. Afterward the unit restarted but still the warning lights came on occasionally. Pump motor #2 was disassembled and inspected. Evidence was found where the KOH had corroded the winding insulation and caused a short. Since pump motor #1 was still running warm, a new replacement pump motor was put into the system at the #2 position while motor #1 was put back in its original position. This new pump motor also ran as warm as the old unit and occasionally temperature warning lights were indicated on module 3. Figure 4-1 through 4-3 show the module temperature histories before the 22 January shutdown. Figure 4-4 shows the temperature history of module 3 after the unit was restarted on 25 January. It is evident from Figures 4-3 and 4-4 that a step change had occurred on the temperature readout of this module after the shutdown. Two days later the readout data seemed to be drifting downward to a condition more in line with the conditions existing before the shutdown.

After adding the new pump motor the system was restarted in the automatic mode and operated in the continuous operating configuration until 27 January at which time the cyclic operating configuration was initiated. Operation continued satisfactorily until 1837 on 29 January when the unit shutdown automatically due to an indicated low system pressure. During restart to troubleshoot the problem, module 3 shut the system down for an indicated high temperature. Further investigation revealed that the temperature probe could be shorting to the electrode within the module. The probe was removed from the module and an insulated patch added to the end of the probe to insulate it from the electrode.

FIGURE 4-1

MODULE 1 TEMPERATURE HISTORY

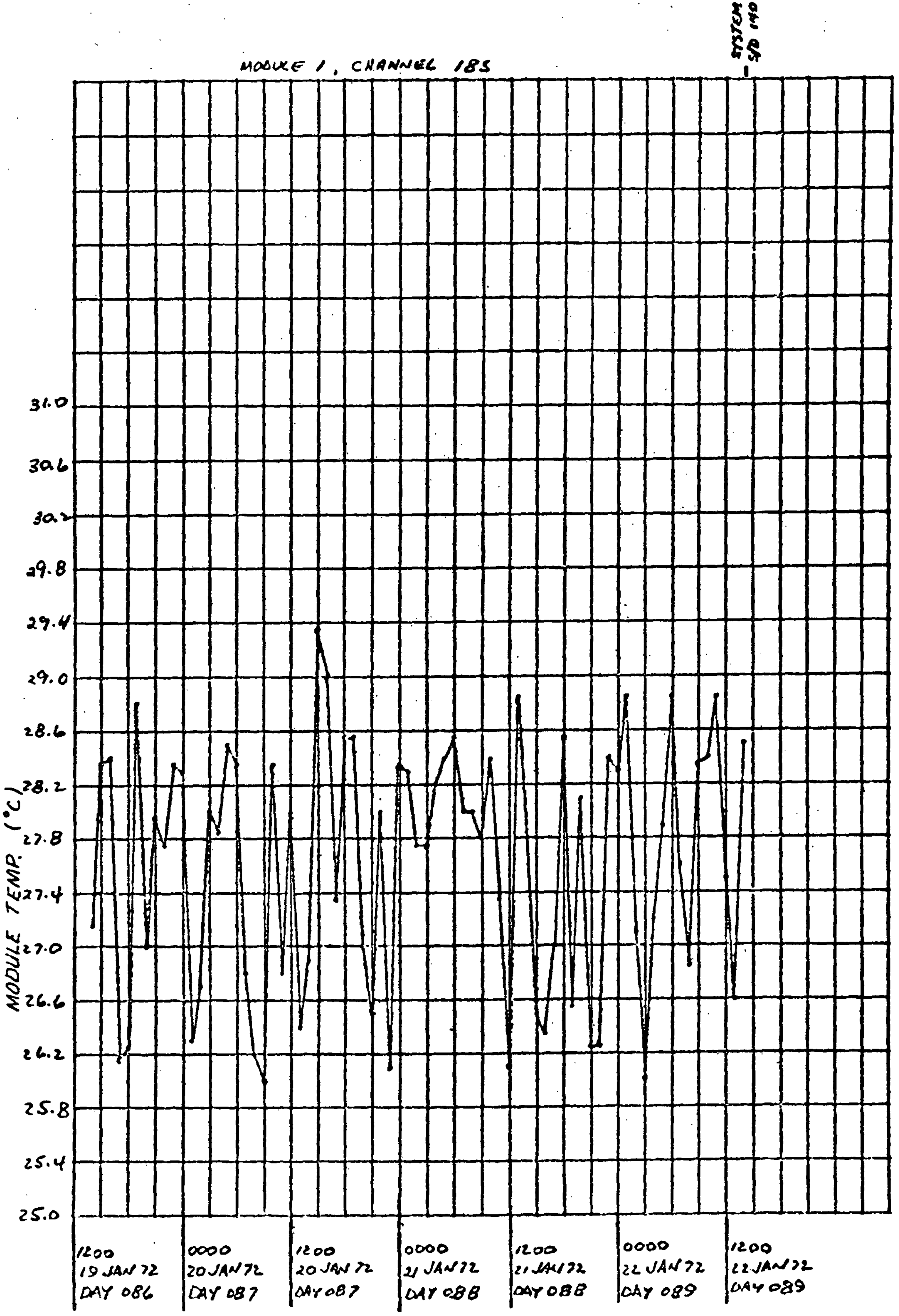


FIGURE 4-2

MODULE 2 TEMPERATURE HISTORY

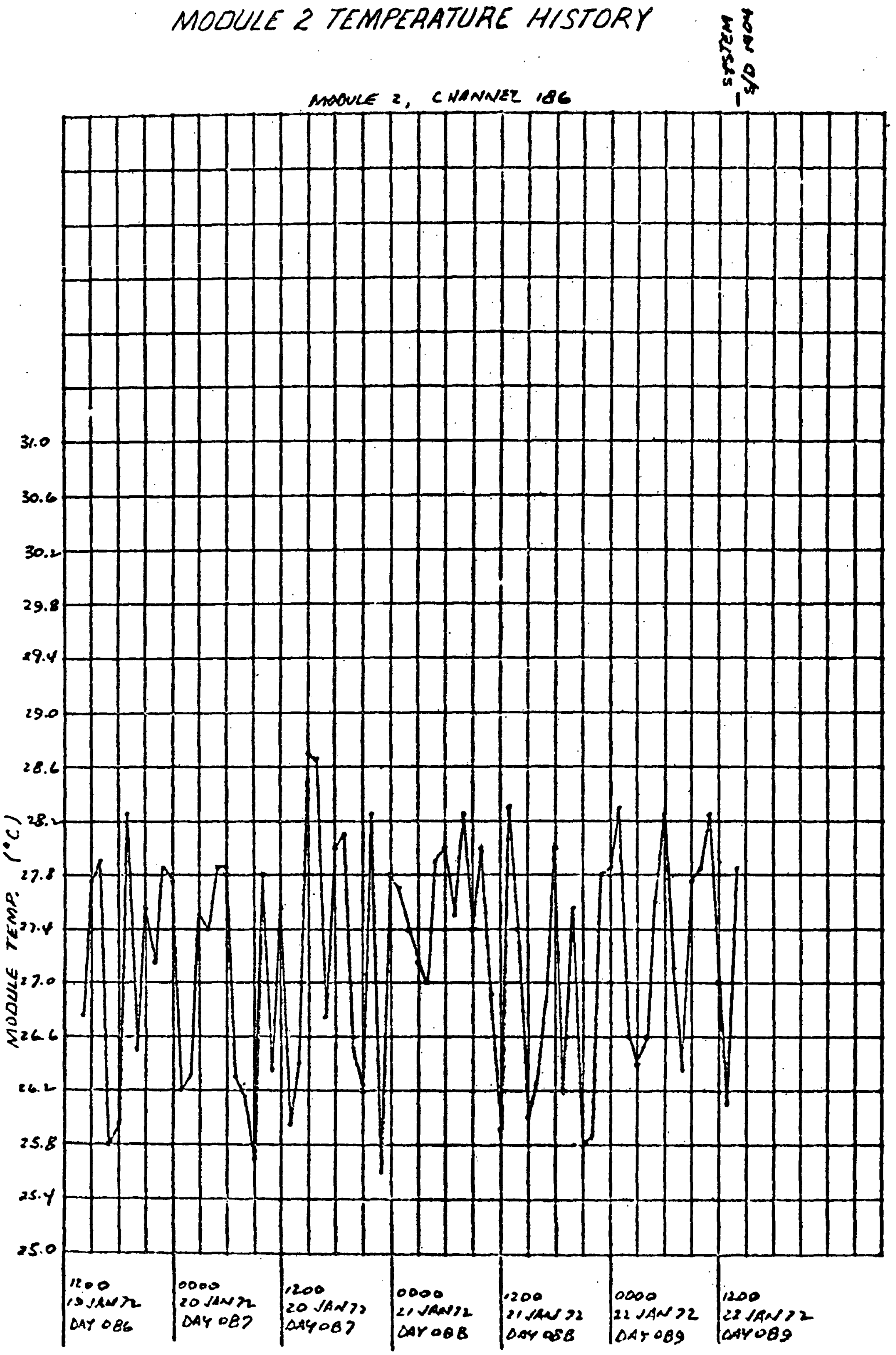


FIGURE 4-3
MODULE 3 TEMPERATURE HISTORY

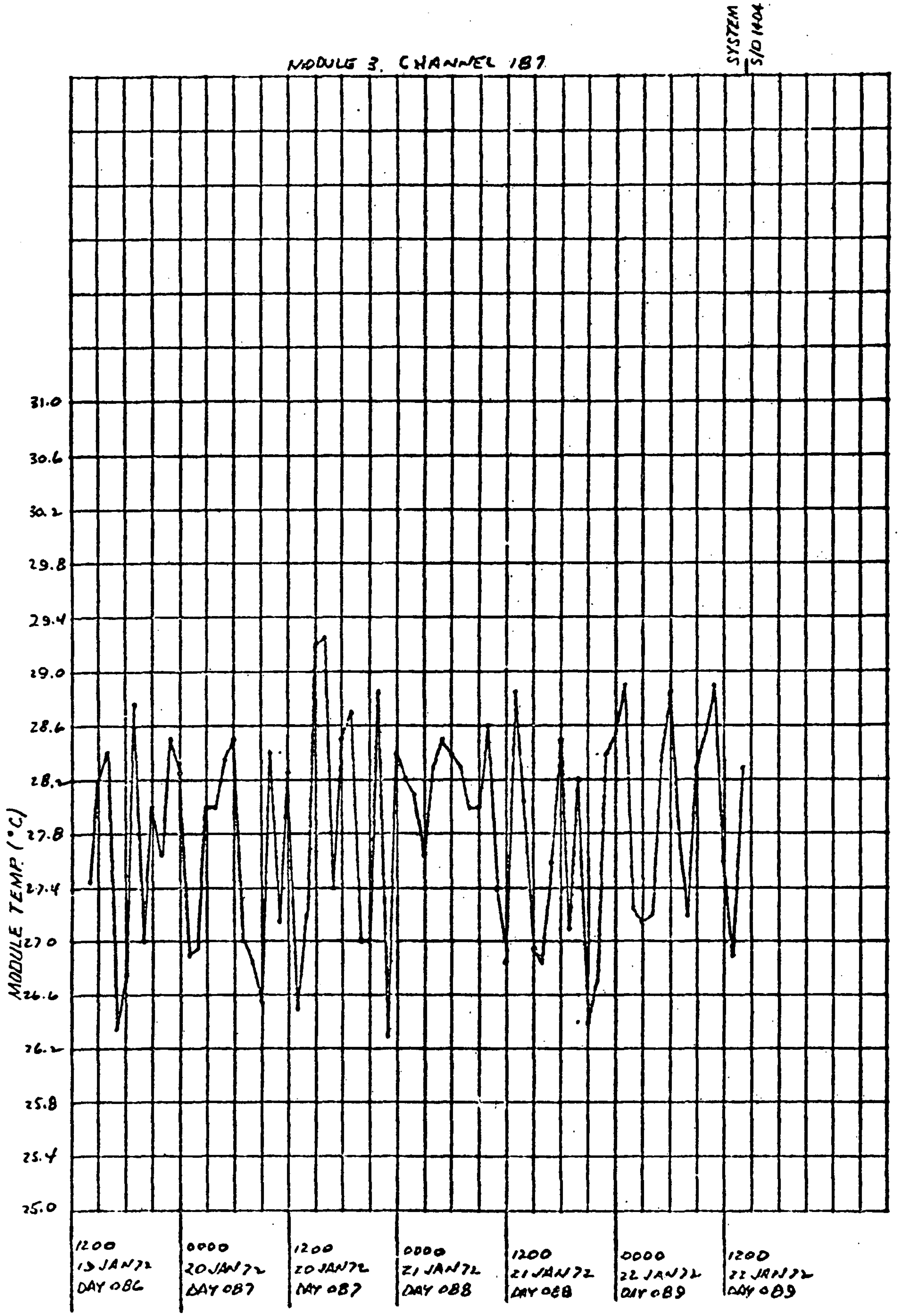
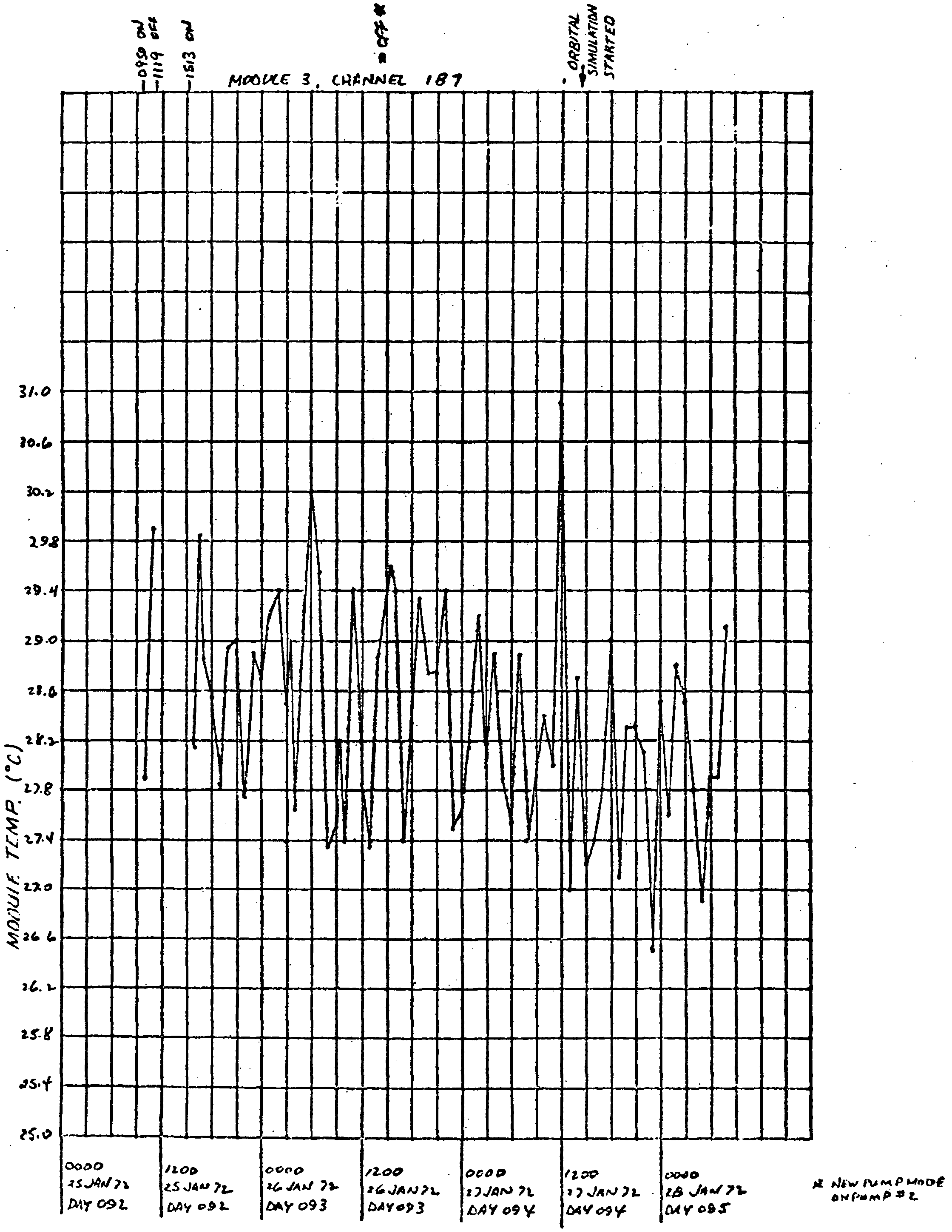


FIGURE 4-4

MODULE 3 TEMPERATURE HISTORY



* NEW PUMP MODE ON PUMP #2

On 1 February the system was restarted after reinstalling the temperature probe and put in a cyclic mode of operation to see if the problem of low system pressure had been resolved. No additional information was obtained but the unit was put in continuous mode for the overnight period as a precautionary measure. The next day the unit was again put in cyclic mode to continue diagnosing the cause of the low system pressure shutdown. It was noticed that the module 3 temperature probe was again giving erroneous readings. The probe was disconnected until a new one could be installed rather than have a shutdown occur due to a faulty probe. That evening the unit was placed in continuous mode of operation for overnight, but at 1811 the system shutdown with no fault indicated. Test point #3 on the recorder was observed to be very noisy. This test point indicated the status of the "On/Off" gate of the electrolysis system.

On 3 February the system was operated intermittently in continuous mode to diagnose the cause of shutdown. No specific cause could be found. Module 4 was found to be not operating. This was resolved when it was found that the coax connector for the module had worked loose on the cable. The unit was shutdown overnight pending modification to be made the next day. On 4 February the integrated circuit chip Z1 on card W2 was replaced. The system was restarted and operated until it was shutdown manually on 4 February to add a modification to the circuit on card SC6. This was to extend the purge period during cyclic mode changes so that pressure would not drop and cause a shutdown. The system was restarted, it operated a few hours and then shutdown automatically. A problem existed in the new circuit added to card SC6. The system was restarted and operated overnight in a continuous mode. On 5 February the unit was shutdown by the resident engineer to make additional modifications to circuit card SC6. A malfunctioning part had to be replaced and a circuit filter added to eliminate noise. At 1545 the unit was back in operation in cyclic mode and continued to operate in that mode for the next week without any problems. Figures 4-5 through 4-10 show data plotted during the orbital simulation period of operation. Figures 4-5 through 4-8 are for each module during the period 6 through 11 February. Figure 4-9 represents five hour periods for each module on 12 February and Figure 4-10 shows one minute data for a single simulated orbit between 1030 and 1225 on 8 February.

FIGURE 4-5

MODULE I ORBITAL SIMULATION DATA

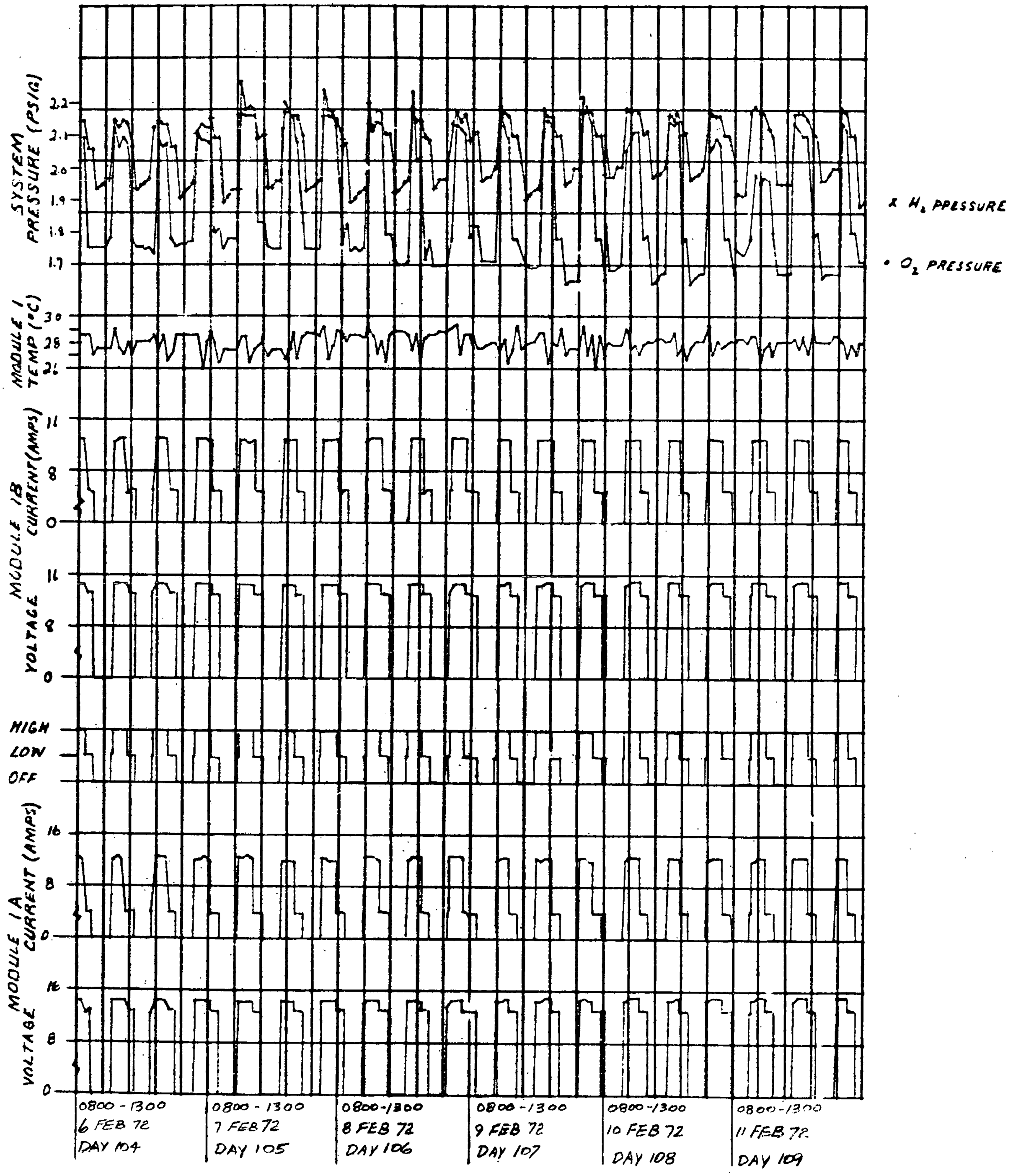


FIGURE 4-6

MODULE 2 ORBITAL SIMULATION DATA

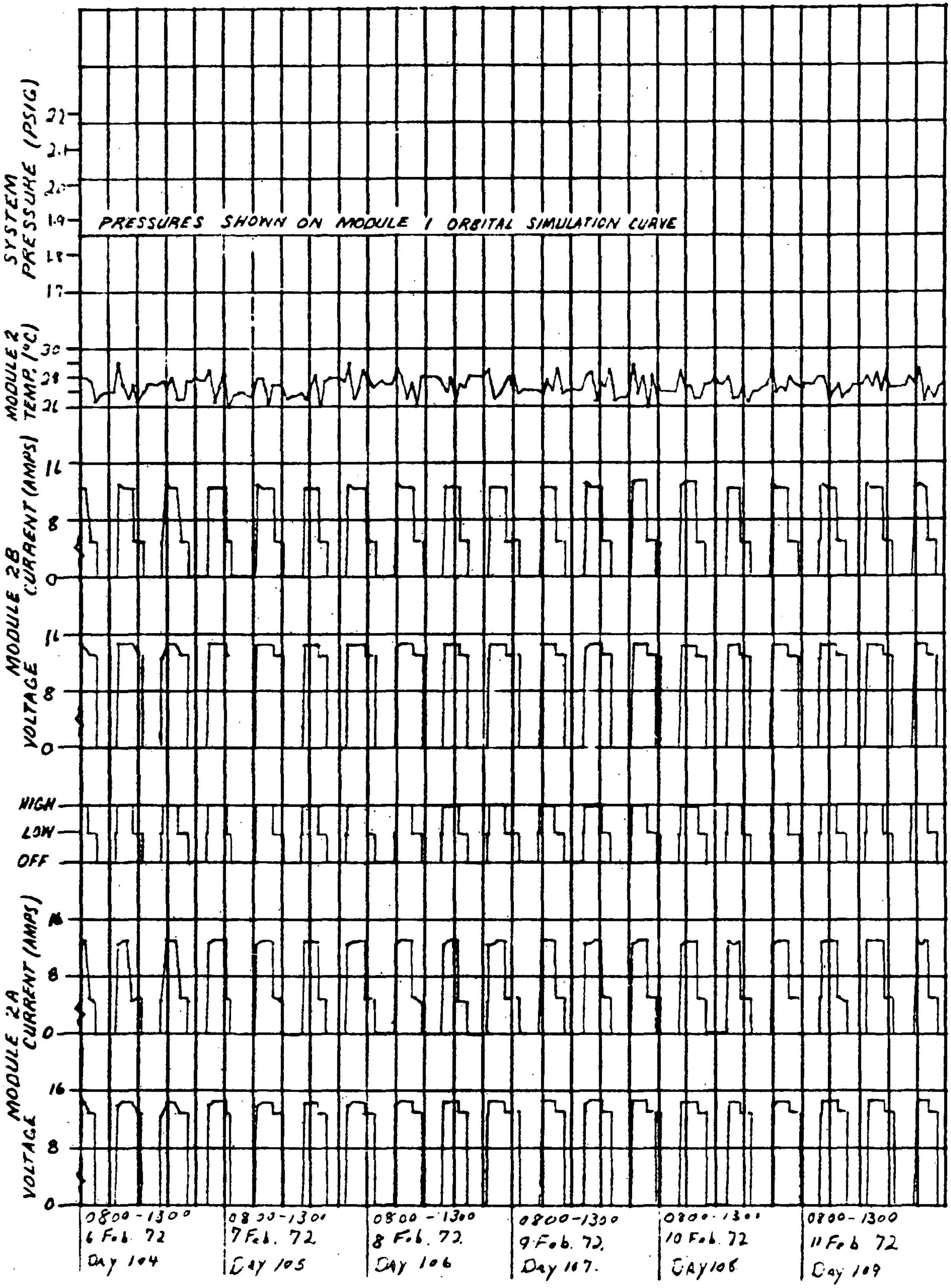


FIGURE 4-7

MODULE 3 ORBITAL SIMULATION DATA

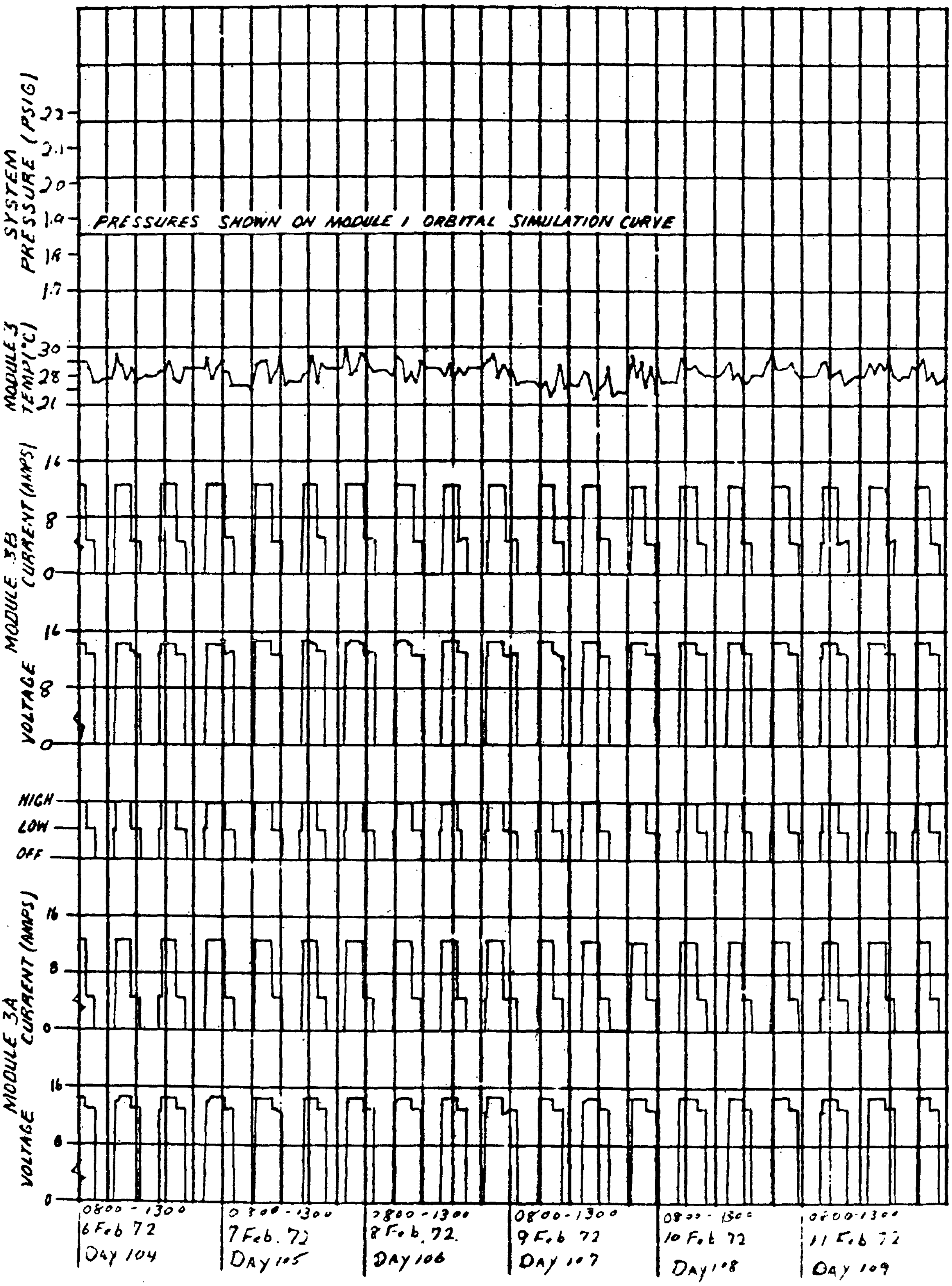


FIGURE 4-8

MODULE 4 ORBITAL SIMULATION DATA

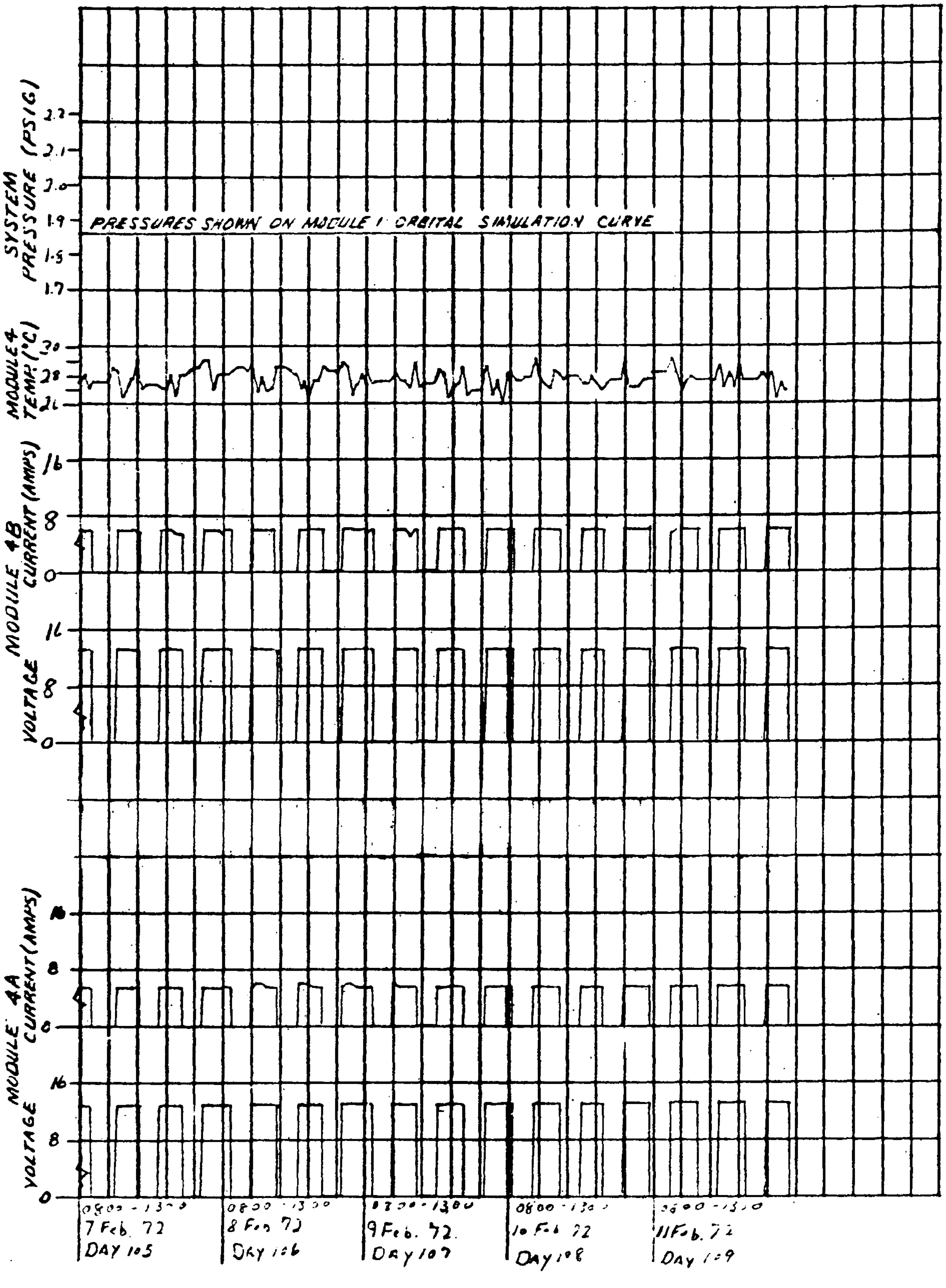


FIGURE 4-9

MODULE 1, 2, AND 3 ORBITAL SIMULATION DATA

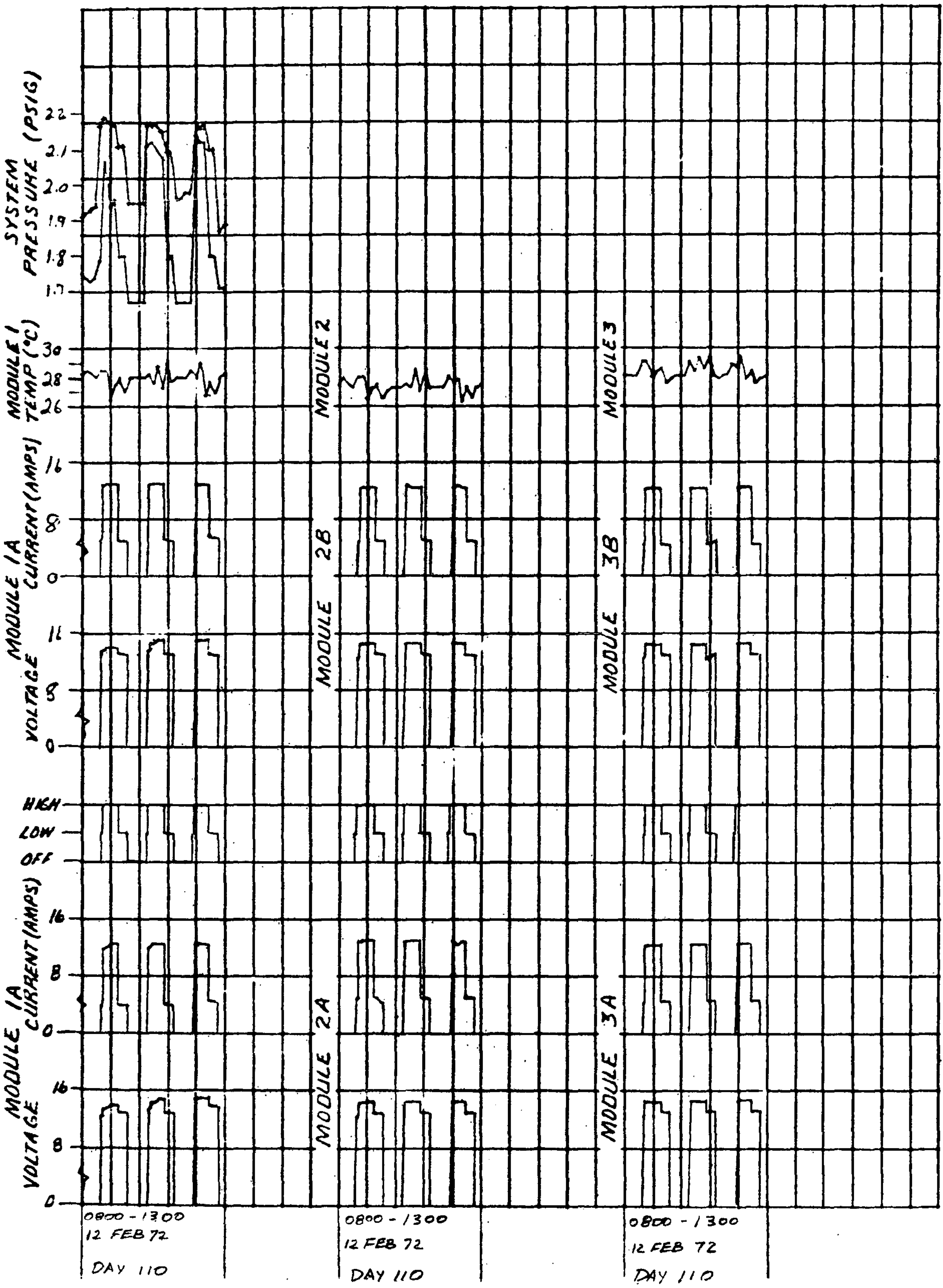
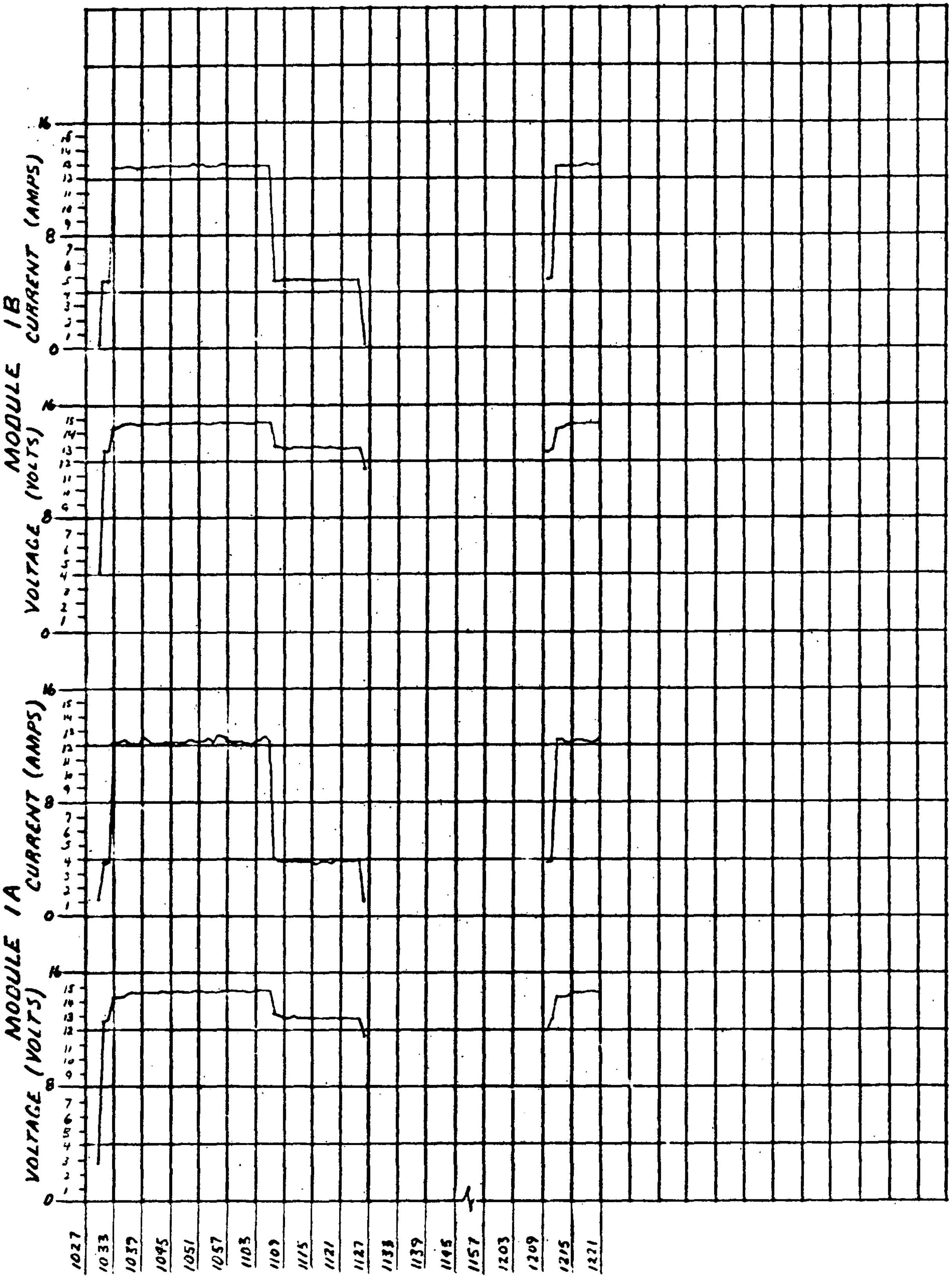


FIGURE 4-10
MODULE 1 ONE MINUTE ORBITAL SIMULATION DATA



ONE MINUTE DATA
1027 THRU 1221 8 FEB 72
TEST DAY 106

On 15 February an electrolyte leak was discovered on the module 3 outlet port of the flowmeter at the 0.64 cm (1/4 inch) feed-through point. The leak was observed for 40 hours with no evidence of any change in leak rate. At 1600 on 16 February it was decided to shut the system down and drain the electrolyte. It was decided to replace all 0.64 cm (1/4 inch) plastic feed-throughs with Teflon-coated stainless steel fittings. The modification was complete, the system recharged with 30.5% KOH and the unit restarted at 1139 on 18 February.

On 22 February at 1201 the timer was reset so that oxygen generation rate would be 3.86 kg/day (8.5 pounds) per day instead of 3.63 kg/day (8.0 pounds) per day. Each day thereafter the timer was readjusted to increase the oxygen output upward another 0.23 kg/day (0.5 pound per day). On 25 February a generation rate of 4.54 kg (10.0 pounds) of oxygen per day was reached. On 26 February at about 0512 module 3 circuit breaker tripped causing shutdown of module 3. The cause of the shutdown was not known. At 1100 on the same day the total system shutdown with no fault indicated. Trouble shooting was performed and it was decided to change the current regulator card on module 3 with a spare card. This card did not seem to completely eliminate the problem. A random noise generator was used to impose signals on circuit card W2 chip Z1. The tests showed that noise was causing the shutdown and it was decided to add a filter capacitor to the circuit. Investigation revealed that the filter had been omitted during refurbishment of the system. It was also felt that previous unexplained shutdowns could be attributed to not having a noise filter on this circuit.

The system continued to operate trouble-free until 7 March when module 4 would not turn on. Some preliminary checks were performed to attempt to diagnose the problem. The checks did not indicate any cause. On 8 March module 4 turned on without any problem. During that day additional tests were made to try to get the module to repeat the failure. The failure could not be duplicated. It was decided to operate module 4 without shutting the system down and trying to find the problem. The decision was based on the relatively short duration of testing remaining and, since the problem was within the electronics and not the electrochemical area, no harm could be done to the system. On 27 March, module 4, after operating all day, would not shutoff at the on/off/standby switch. The module was finally shutoff at the circuit breaker. Again, on the following day the problem had cleared itself. Some troubleshooting was performed but no positive cause was found. On 3 April the production rate was reduced from 4.54 Kg/day (10 pounds/day) to the nominal value of 3.63 Kg per day (8 pounds per day) oxygen generation rate. Module 4 on/off/standby switch continued to stick in standby mode or off, thus the module was controlled by the circuit breaker rather than the normal switch. The system operated until the termination of testing at 1200 on 25 April without any additional problems.

Figures 4-11 through 4-14 show the overall performance of the system for the entire duration of performance-endurance testing. Summary notations also show the cause of or suspected cause of each system shutdown that occurred. The longest uninterrupted period of performance for modules 1, 2 and 3 occurred from 3 March to the end of testing, 25 April, a period of 53 days. The modules were all operating properly at the end of the test.

Figure 4-15 shows the scheduled and actual O_2 production during the test period. The decrease in production rate on the CEU after day 26 was a direct result of the decision to shut down module 4 when the unit was unattended. There was no evidence throughout the 26-week test period to indicate module 4 operating characteristics were in any way different from the other 3 modules. On that basis, it is assumed that module 4 would have operated throughout the test. This unit was able to maintain required production rates of 3.63 Kg/day (8 lb/day) and 4.54 Kg/day (10 lb/day) during attended operation (normal working hours). The drop at day 94 was the initial start of cyclic operation to simulate orbital performance. Problems were encountered and the unit was put on continuous mode until day 103. Cyclic mode was conducted satisfactorily between day 103 and 110. The actual production rate is below the scheduled rate because of the requirement to shutoff module 4 during unattended periods. The gradual rise from day 120 through day 124 was the requirement to increase production

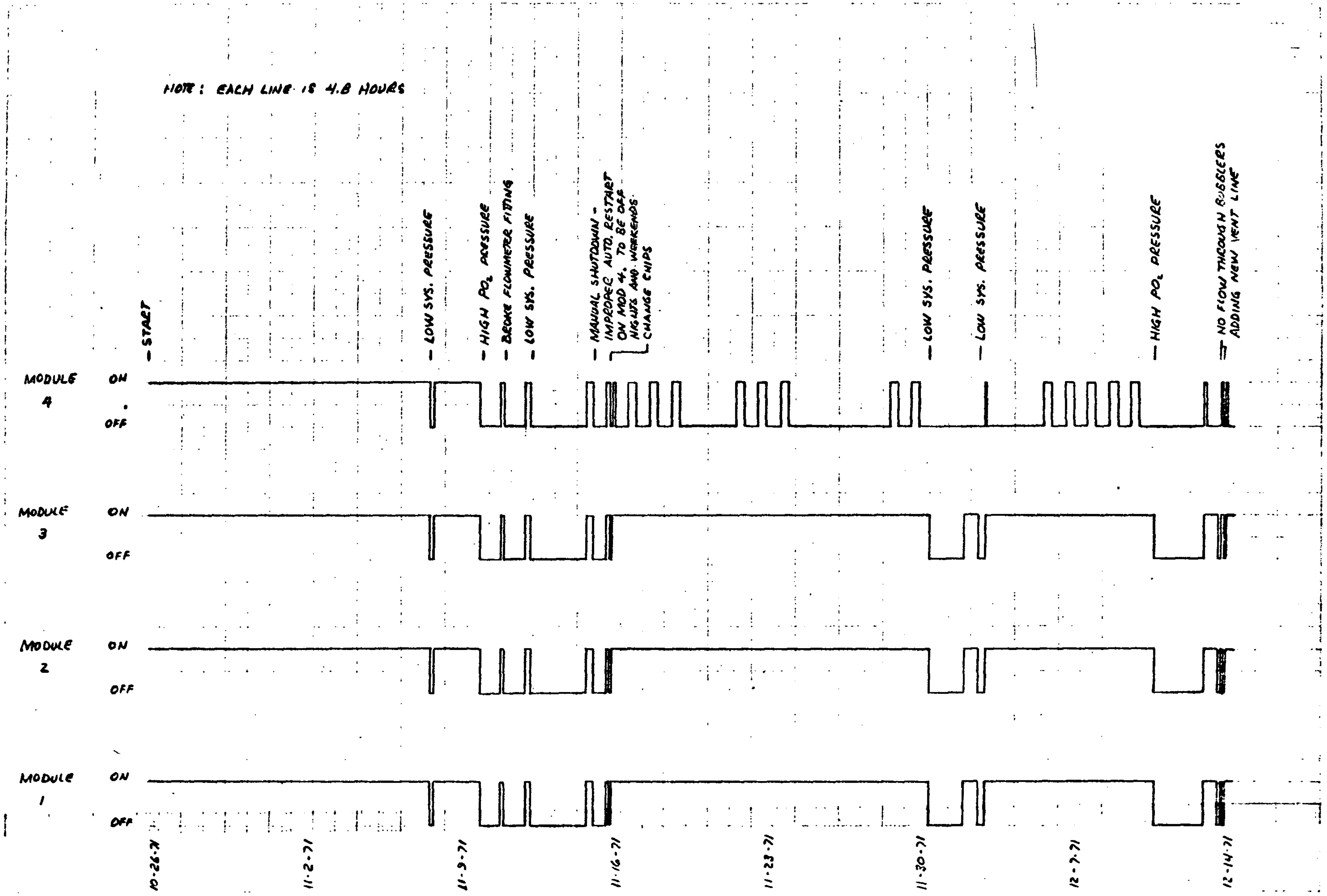


FIGURE 4-11 CEU SUMMARY PERFORMANCE, 26 OCTOBER - 14 DECEMBER

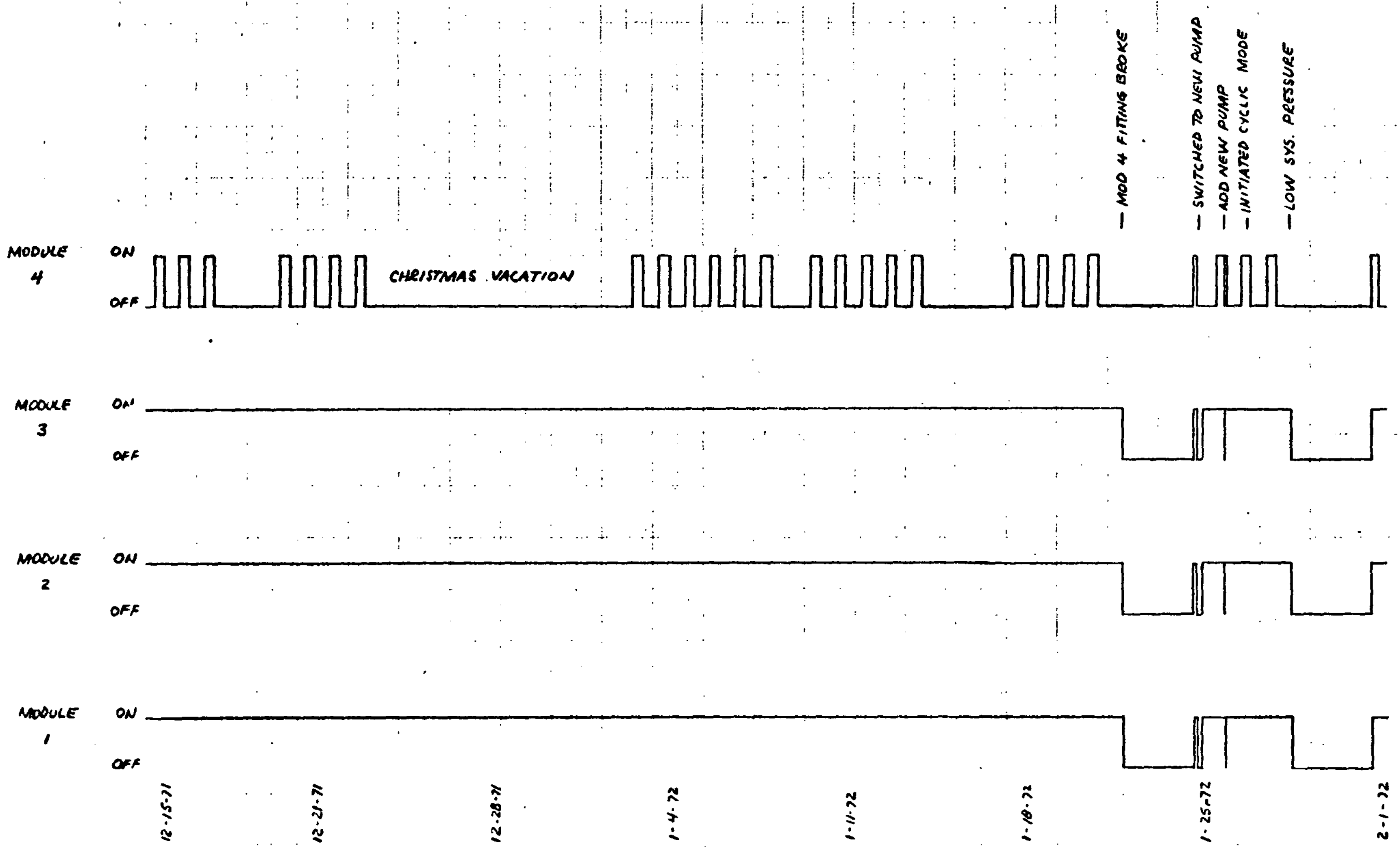


FIGURE 4-12 CEU SUMMARY PERFORMANCE, 15 DECEMBER - 1 FEBRUARY

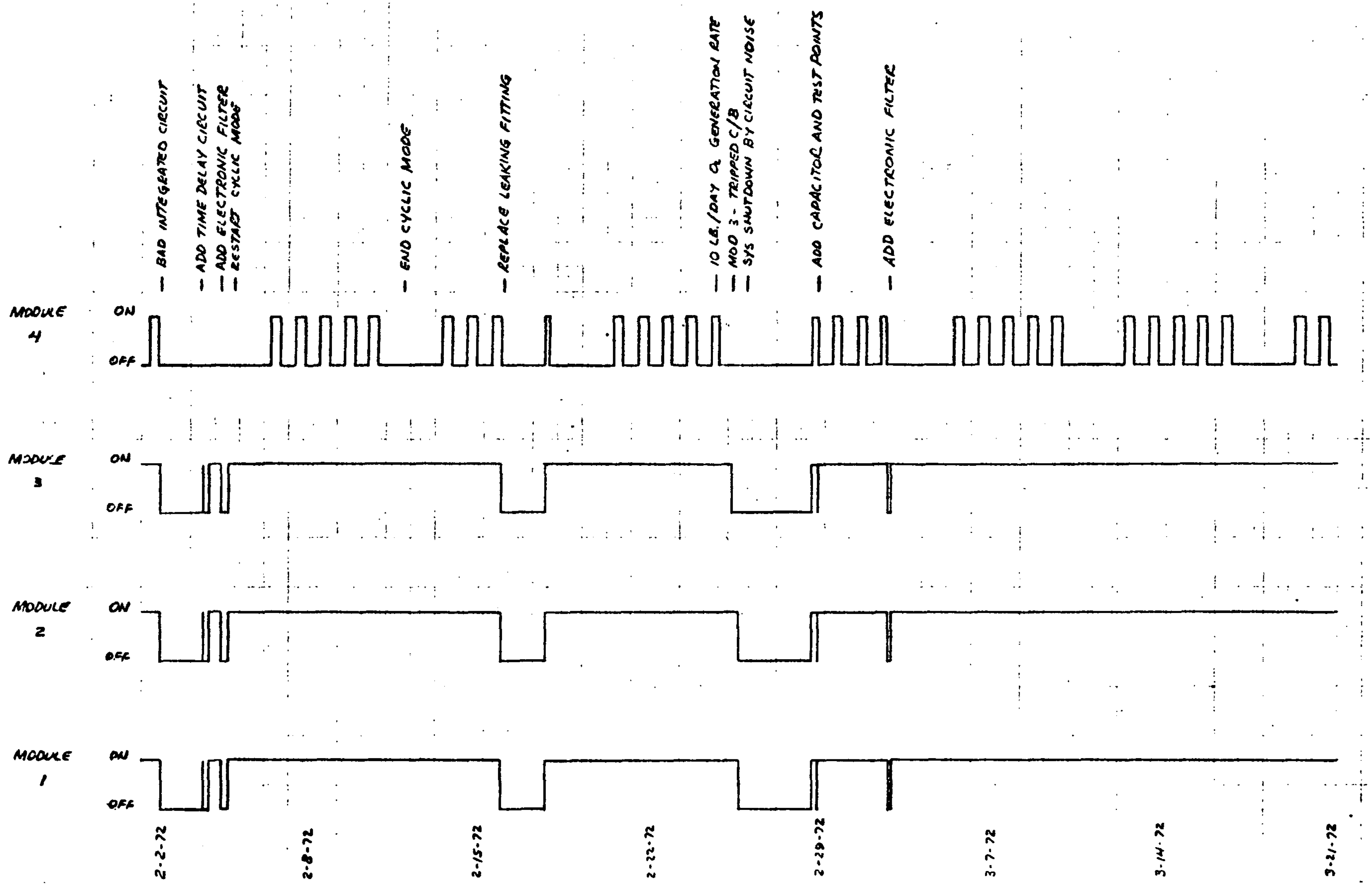


FIGURE 4-13 CEU SUMMARY PERFORMANCE, 2 FEBRUARY - 21 MARCH

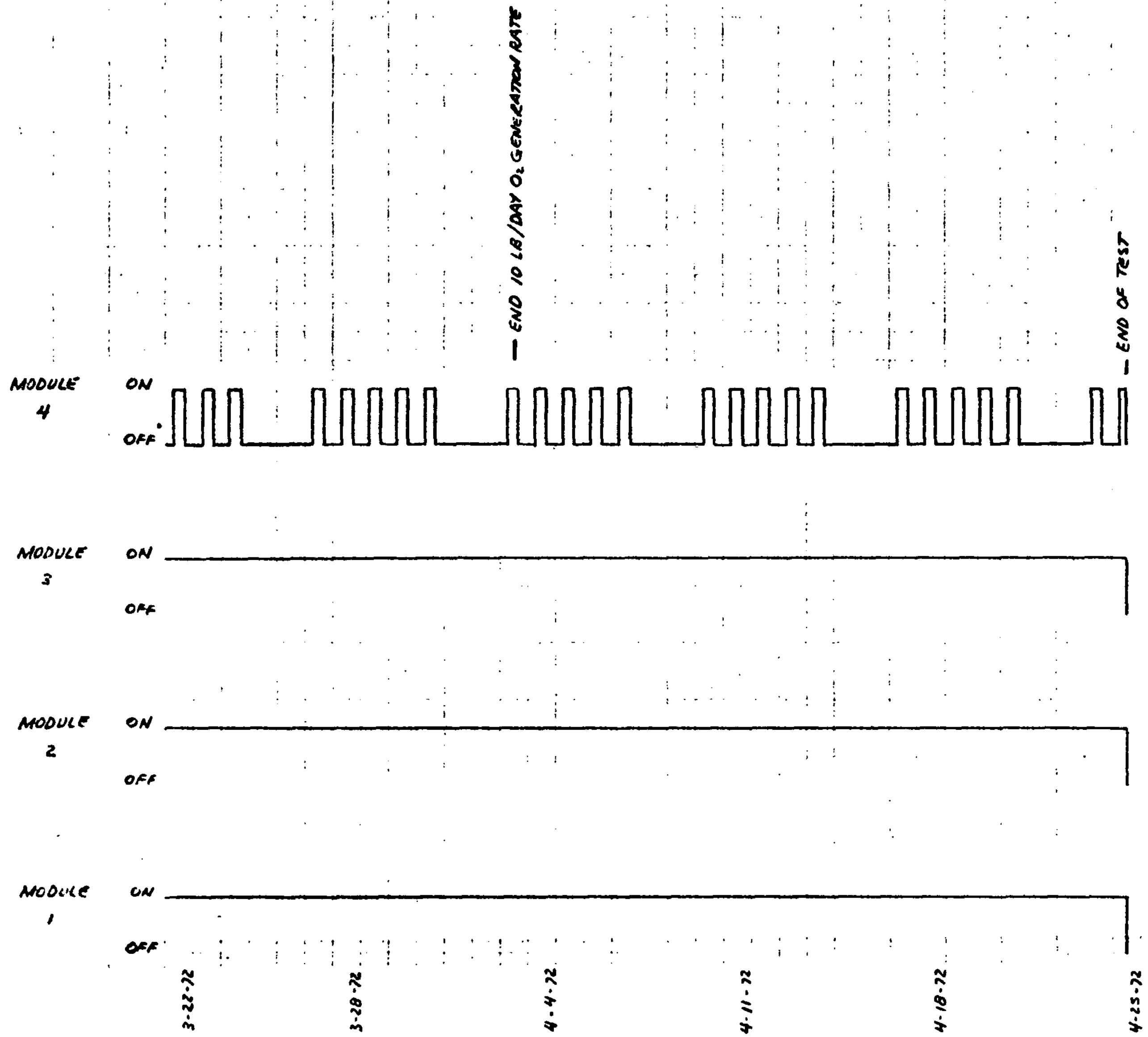


FIGURE 4-14 CEU SUMMARY PERFORMANCE, 22 MARCH - 25 APRIL

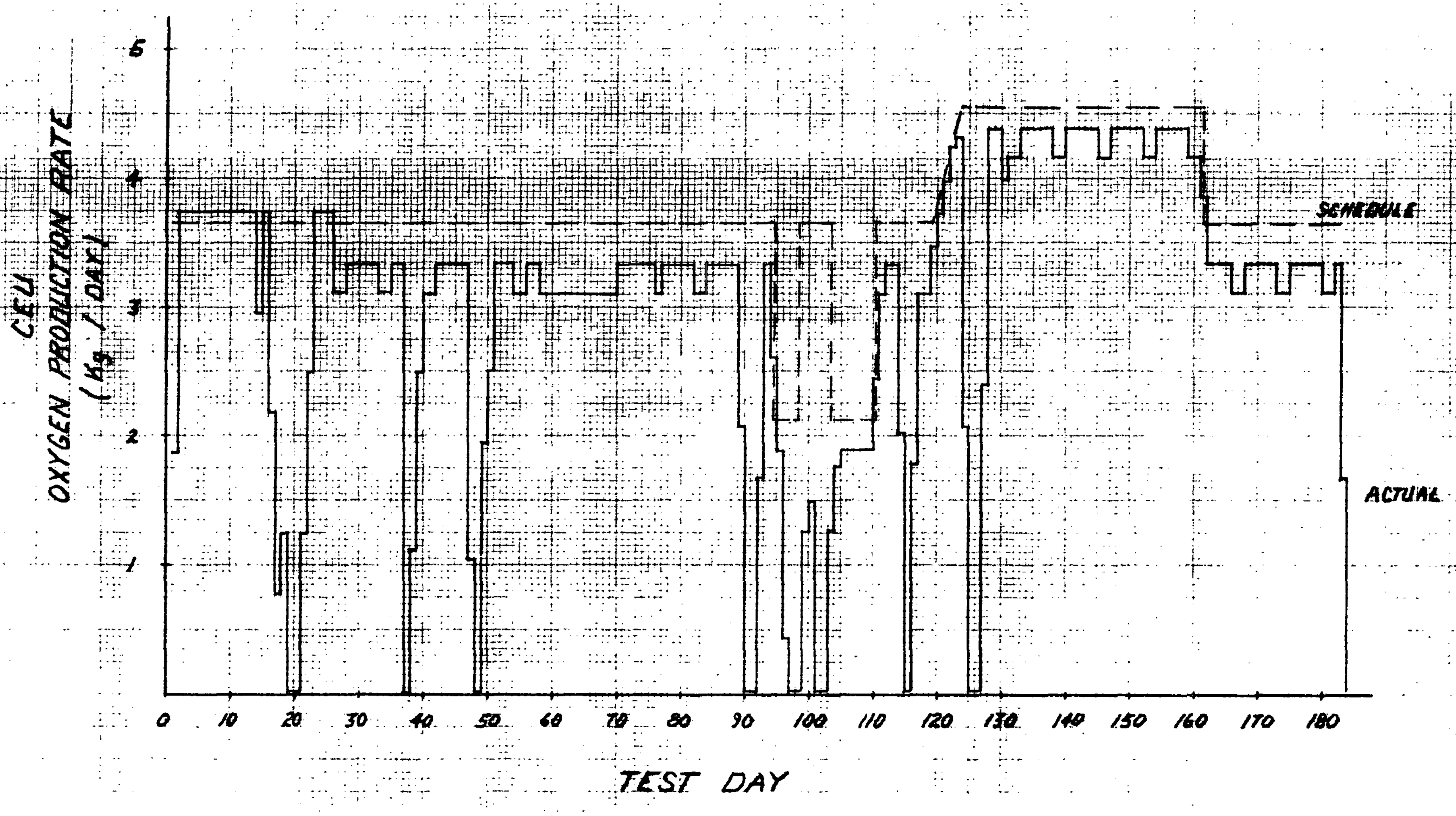


FIGURE 4-15 OXYGEN PRODUCTION RATE COMPARISON

rate 0.227 Kg/day (0.5 lb/day) until 4.54 Kg/day (10 lb/day) rate was reached. Production rates below 3 Kg/day (except for cyclic mode operation) were indicative of system shutdowns, problem troubleshooting and half-day operation on the day 1 and 183.

Figure 4-16 shows the ideal cumulative module test time and actual test time in terms of module hours. The longest period of uninterrupted CEU operating time was 53 days, from day 130 through day 183. The unit also operated uninterrupted for 38 days in the first half of testing, from day 51 to day 88. It is important to note that the amount of down time experienced by both units was considerably larger than one would expect with around-the-clock attendance and the provisioning of ample spare parts. Because of the development nature of this program, the effort was generally limited to 40-hour weeks and only limited spare parts were provisioned. The time attributable to actual labor for repairs of the CEU was estimated to be less than five percent of the total down time. This excludes fault diagnosis and troubleshooting.

The initial scheduled module-hours curve represents four modules operating for 24 hours per day. The percentage of actual cumulative module-hours was influenced by a groundrule established during the test program. The CEU had a problem on the 20th day of test that shut the unit down, but module 4 had several spurious restarts. As a conservative measure, it was decided to turn off module 4 on nights and weekends to preclude any chances of permanent damage to the module. If it is considered that this redefined the ideal module-hours as shown on the revised schedule curve, then the CEU operated for 84.6 percent of this redefined goal through the 26 weeks of testing.

4.3.2 Module Performance

Specific performance of each module bank is presented in this section, Figures 4-17 through 4-70. The curves show operating mode; module bank voltage and current; temperatures of coldplate, electrolyte leaving the

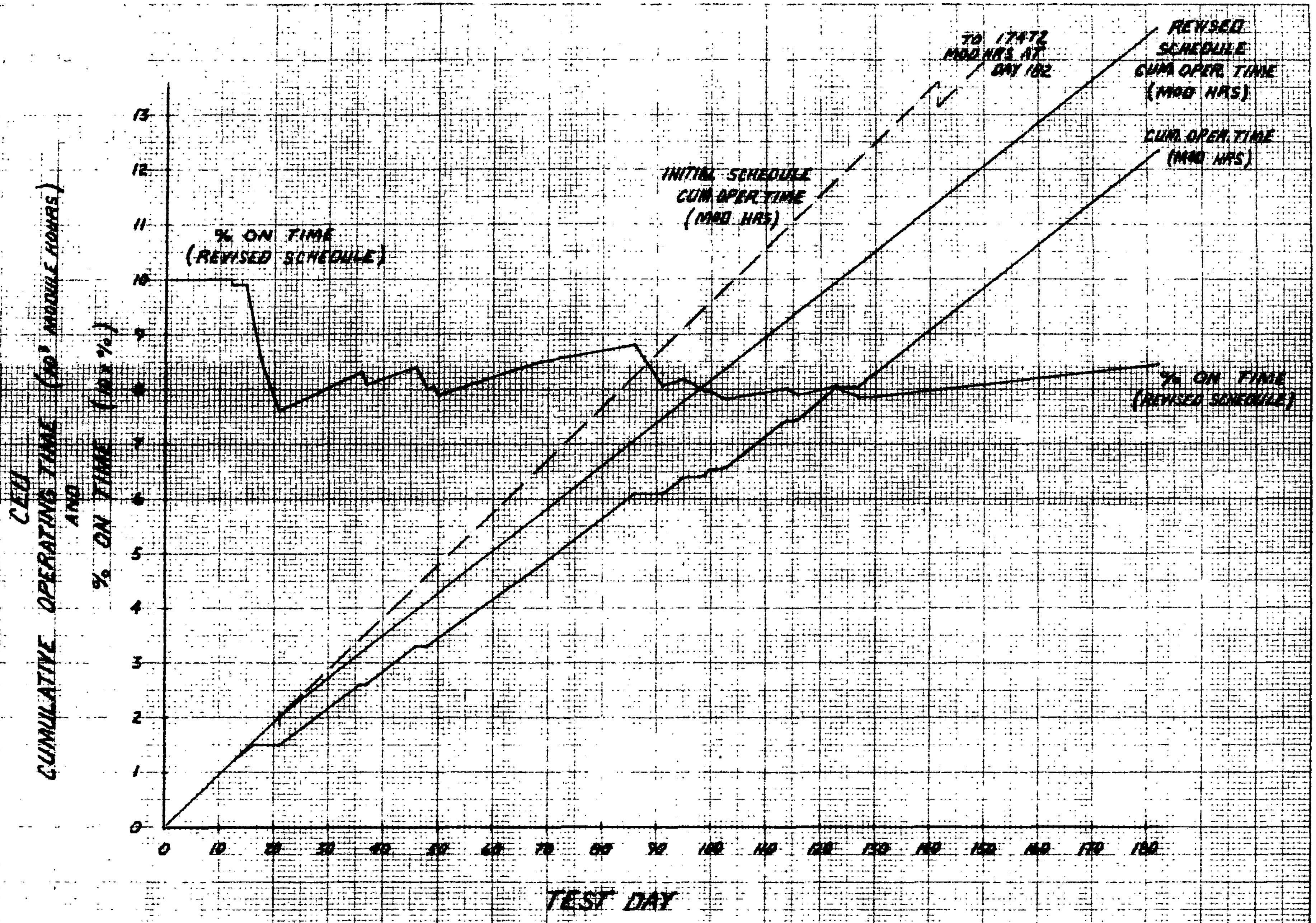


FIGURE 4-16 SYSTEM OPERATING TIME COMPARISON

the heat exchanger, and electrolyte leaving the modules (EL2); and pressures of hydrogen and oxygen. Most of the curves present discrete points rather than connected points because the unit shifted from high mode to low mode at intervals other than when the data was printed by the data system. Each division along the abscissa represents an 8-hour period. Table 4-1 at the end of these curves briefly defines the periods of time when the system was not operating or when the data acquisition system was not operating.

A second set of figures (4-71 through 4-98) included in this section provides daily data from the 24-hour summary printout of maximum, average and minimum voltage of the module; maximum and minimum current; maximum cell voltage for cell number 2 in each cell bank; and maximum module temperature.

The performance degradation at the 3.63 kg/day (8.0 pounds/day) O_2 production rate showed about a 4.5 percent increase in the energy required per 0.45 kg (1.0 pound) of oxygen when compared with the initial value. Most of the observed performance loss was caused by the experimental anodes in module 1. Energy requirements increased approximately 2 percent over the 6 months of operation when considering module 2, 3, and 4 alone (which had the fully developed electrodes). Testing at the maximum oxygen rate of 4.54 kg/day (10 lb/day) produced no significant increase in rate of performance degradation when compared with the 3.63 kg/day (8 lb/day) rate. The initial specific energy requirement was approximately 5 percent higher at the 4.54 kg/day production rate.

A significant result of the testing was the simulated orbital performance of the system (test days 103 through 110). The gas production was cut to zero during the shadow portion of an orbit (38 min.) and production was at design level during the sunlit portion of the orbit (54 min.). During this 1-week test period, 120 orbits were simulated, thereby subjecting the system automatically to 120 changes from zero up to maximum oxygen production and 120 step changes from low-mode current to zero. Module specific energy requirements for cyclic operation were 5 percent lower than for continuous operation because of lower cell voltages. No measurable degradation in performance was observed during the 1-week test period.

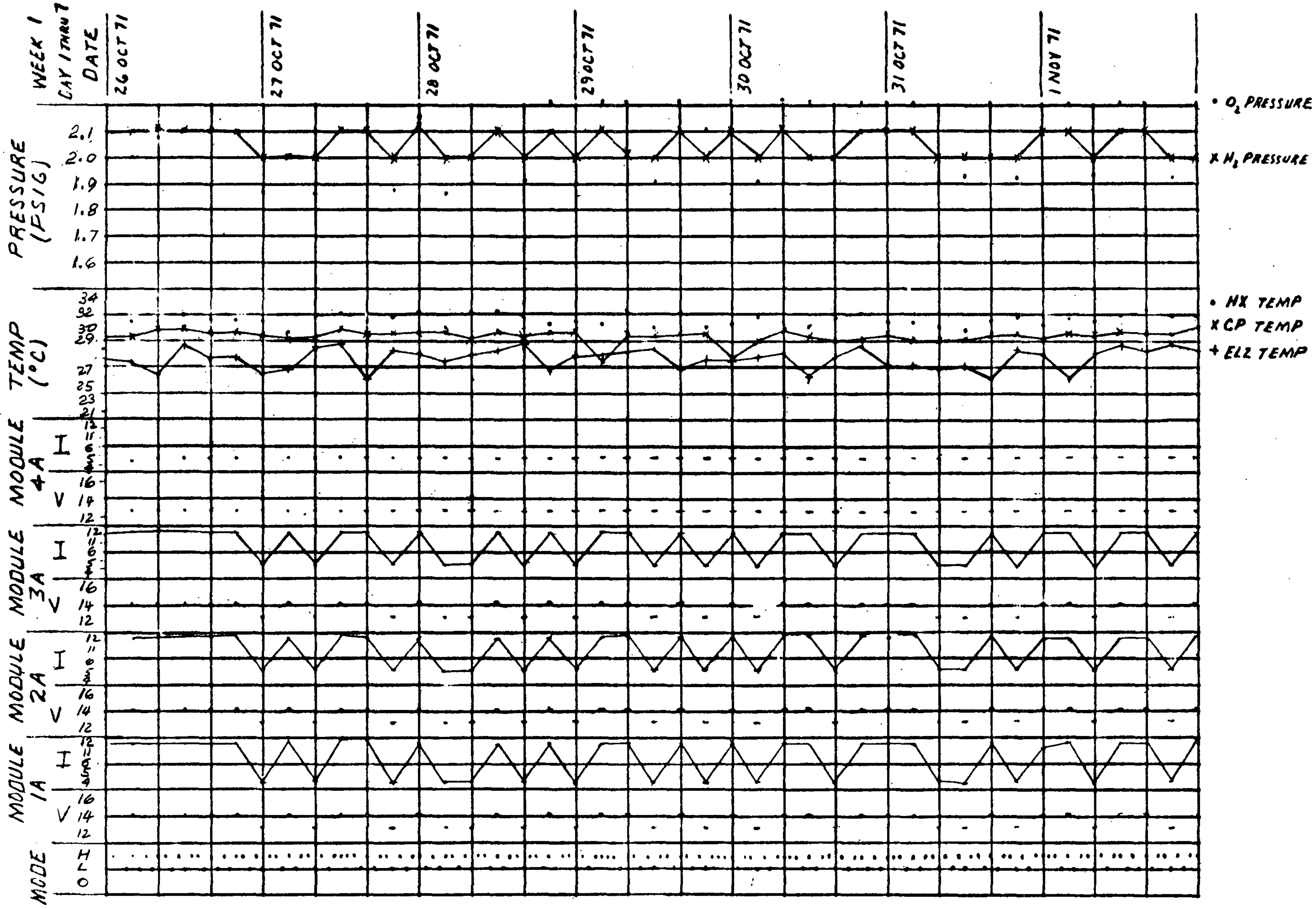


FIGURE 4-17
CEU DAILY PERFORMANCE DATA

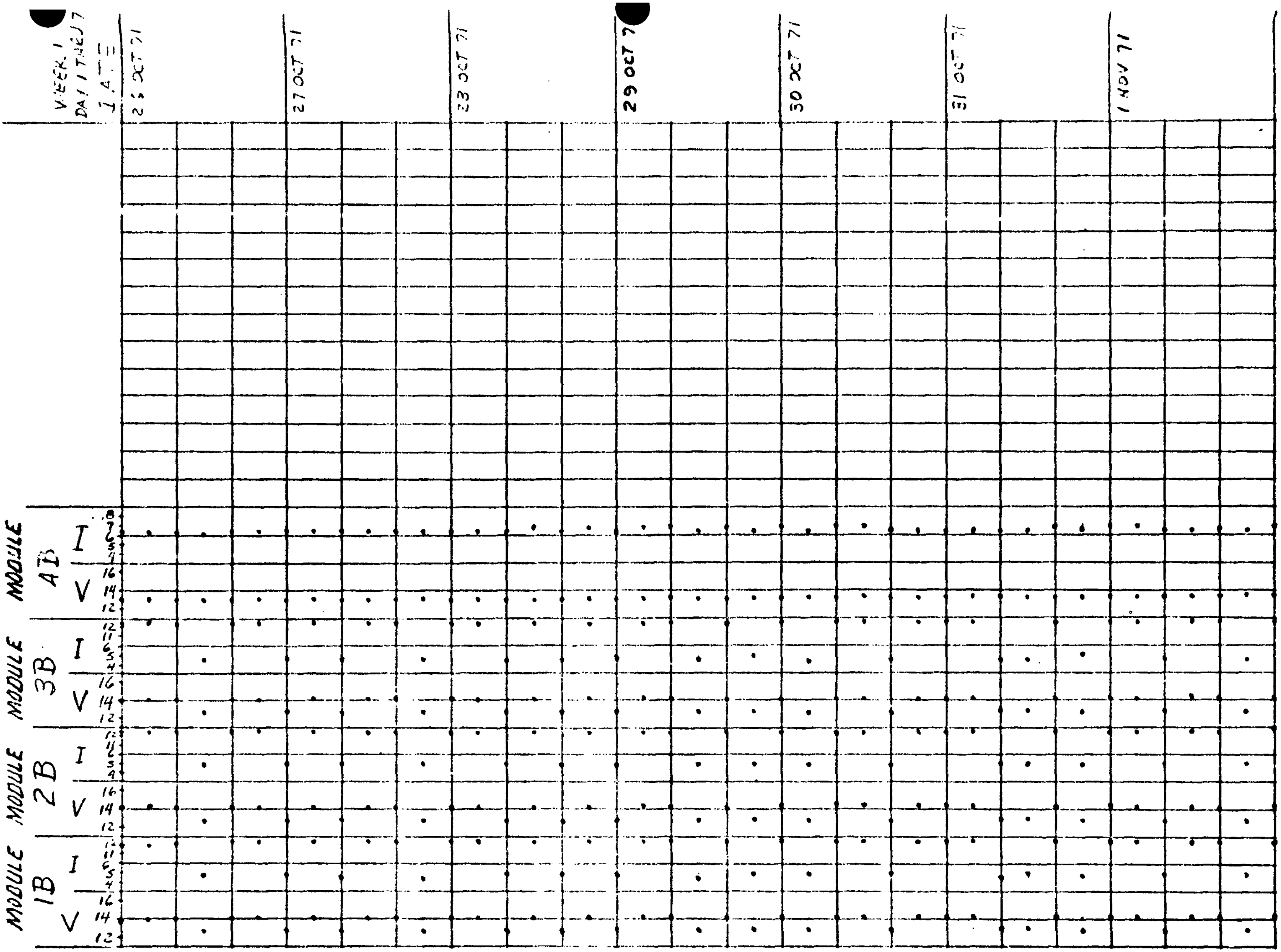


FIGURE 4-18
CEU DAILY PERFORMANCE DATA

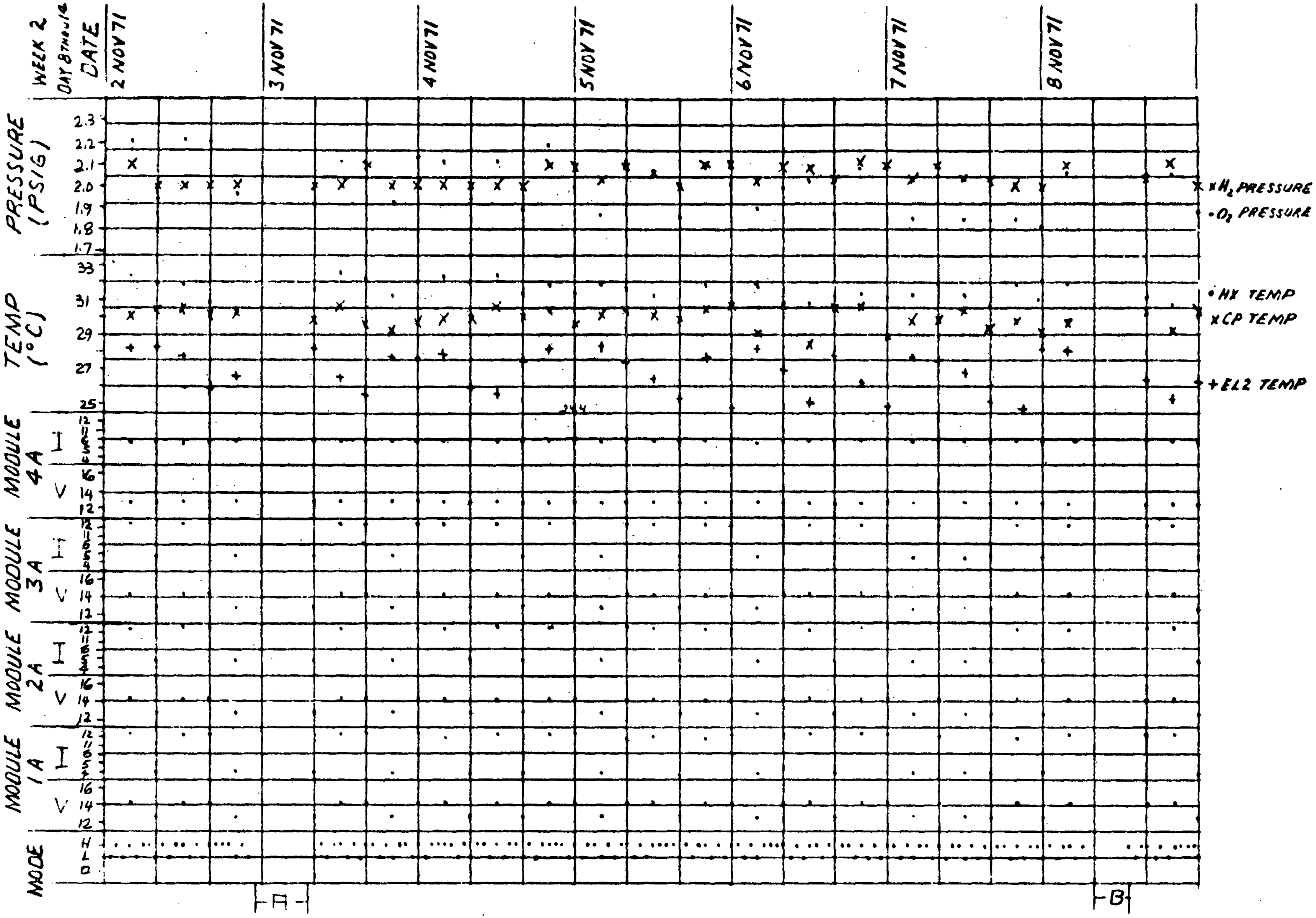


FIGURE 4-19
CEU DAILY PERFORMANCE DATA

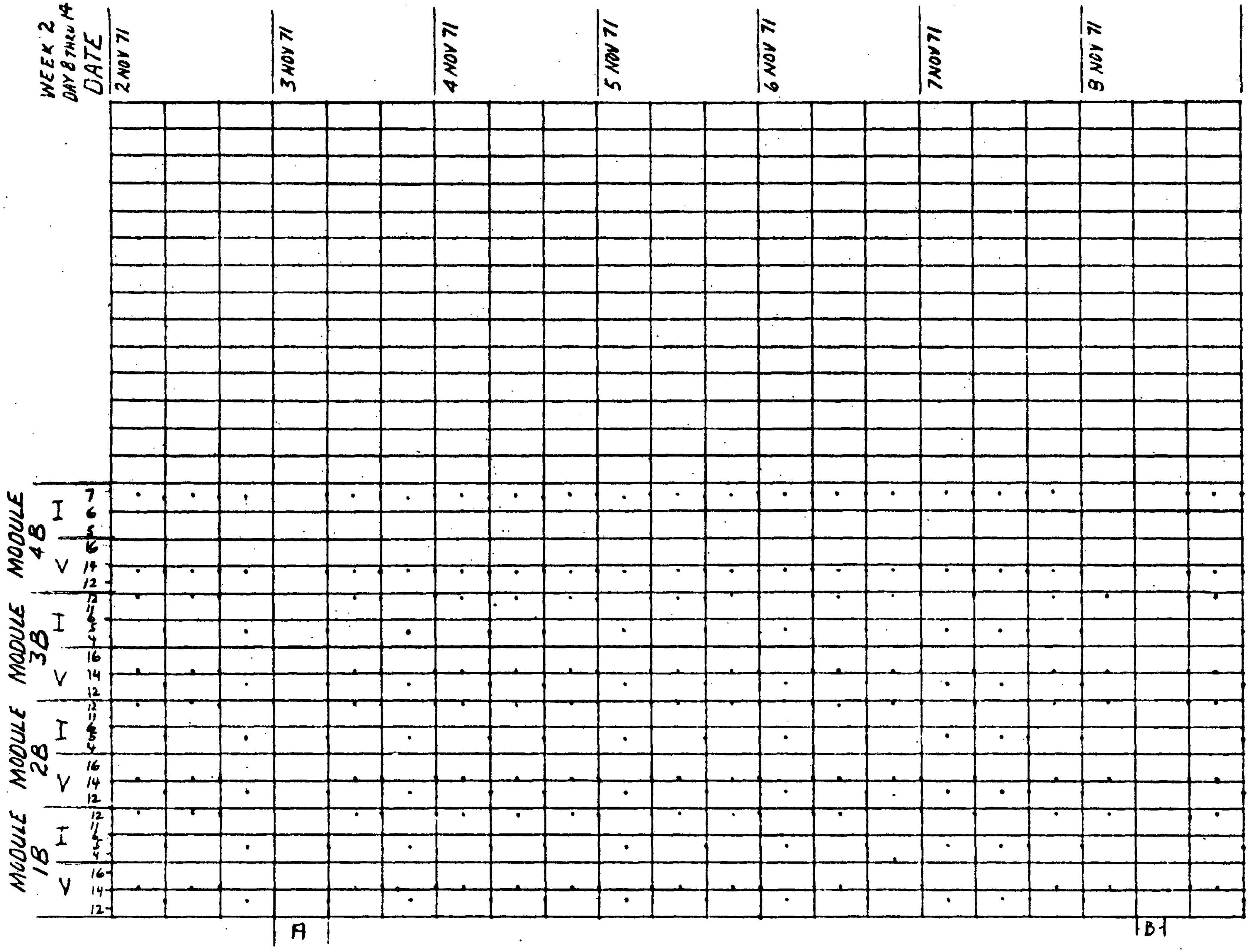


FIGURE 4-20
CEU DAILY PERFORMANCE DATA

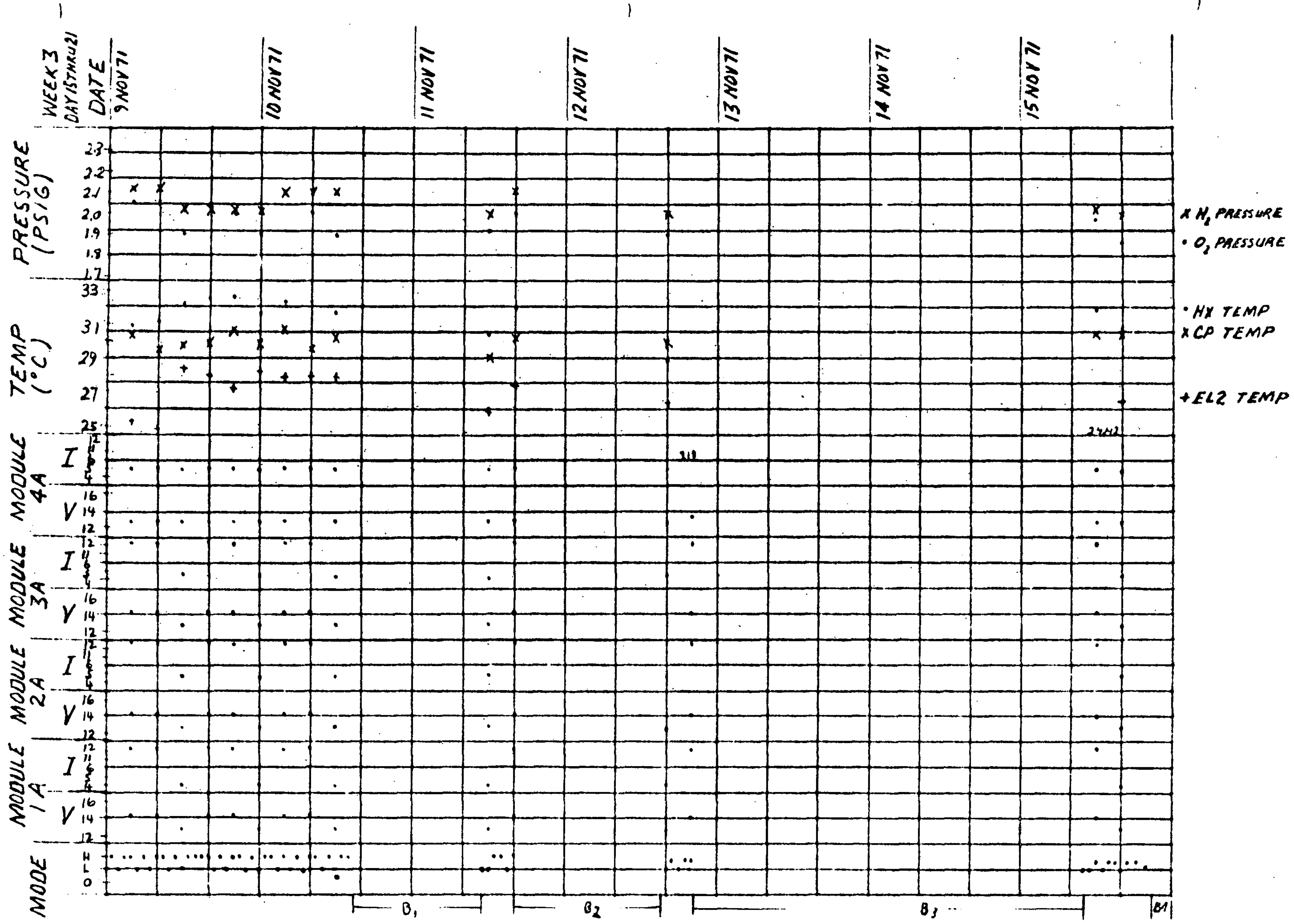


FIGURE 4-21

CEU DAILY PERFORMANCE DATA

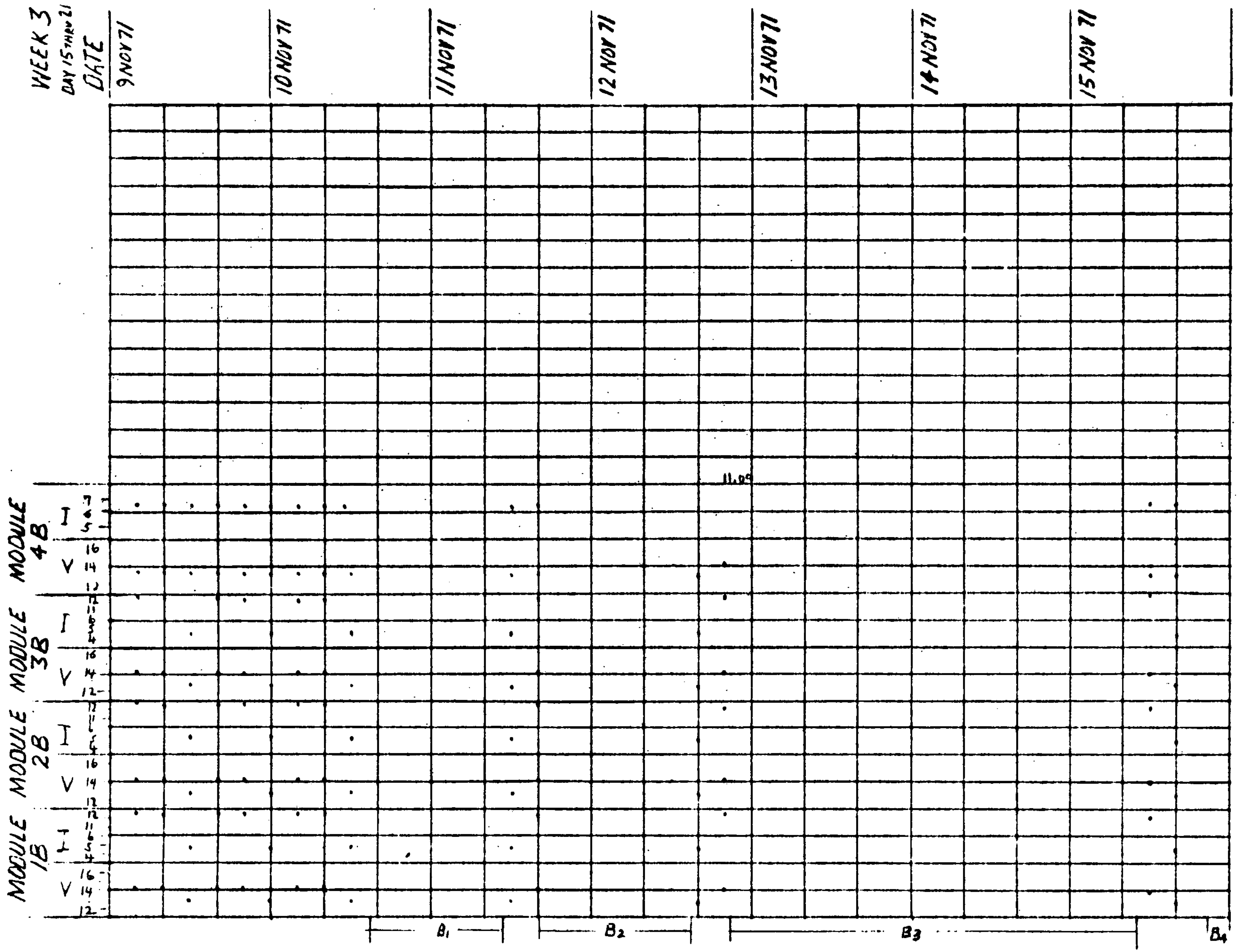


FIGURE 4-22
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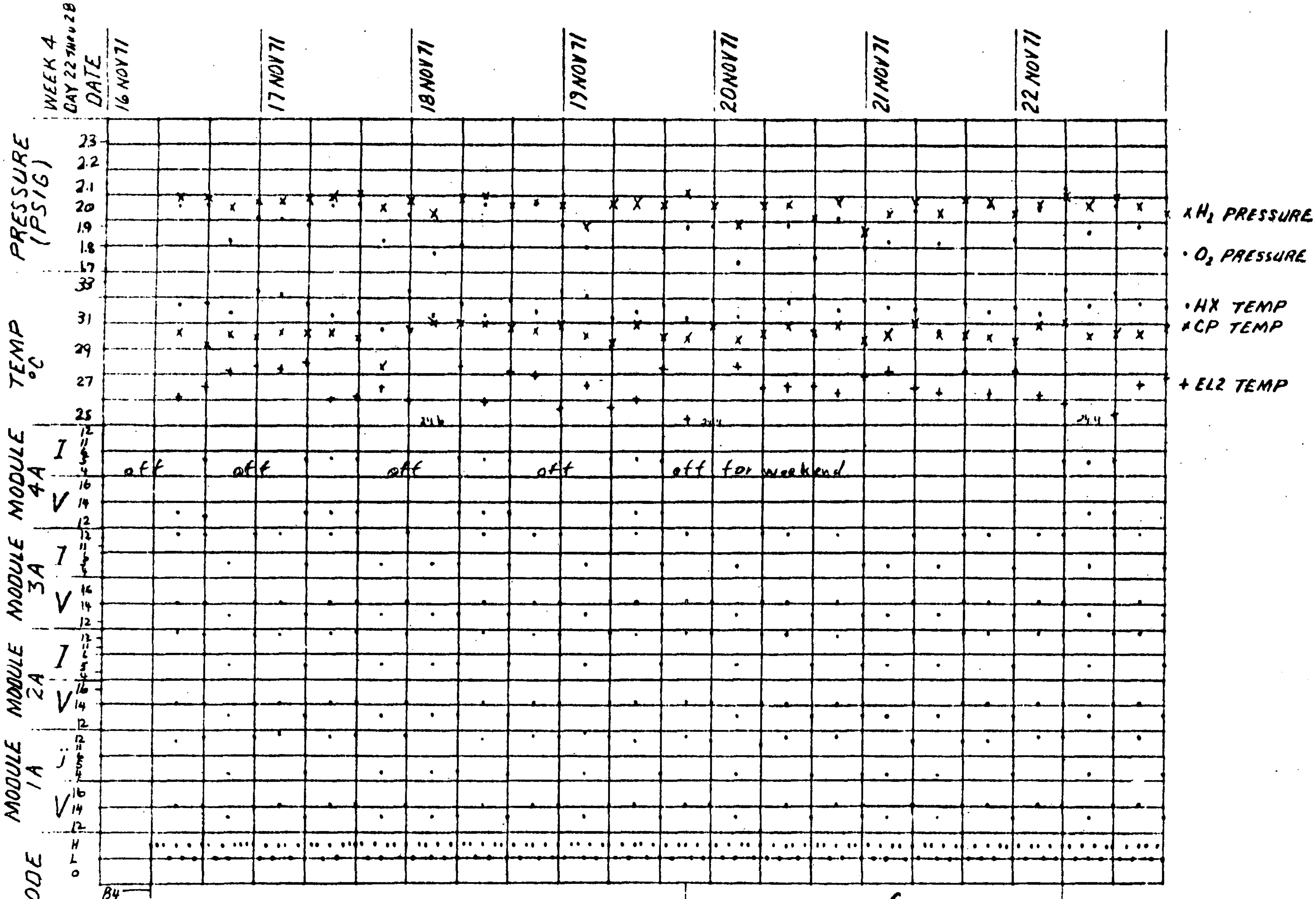

FIGURE 4-23
CEU DAILY PERFORMANCE DATA

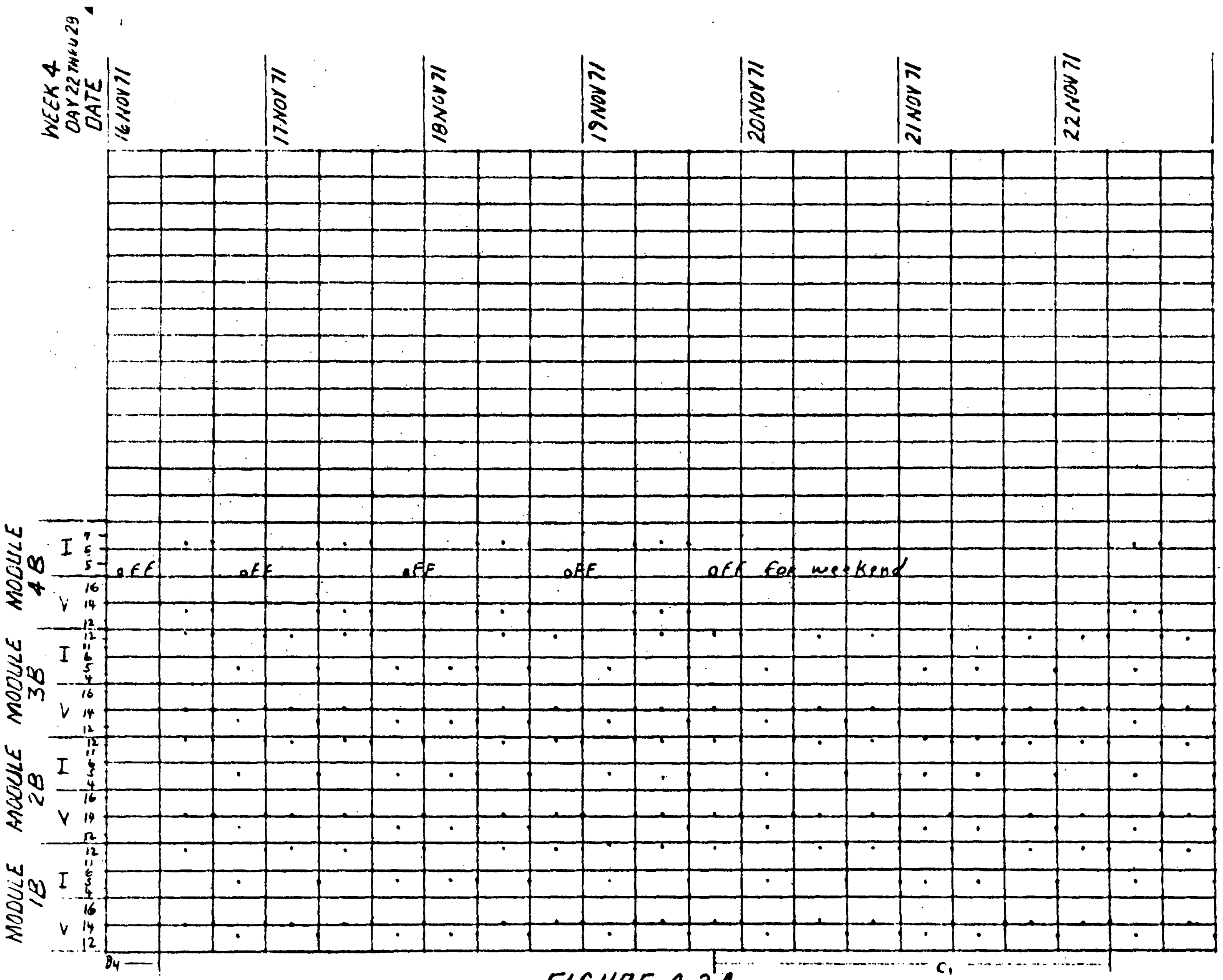

FIGURE 4-24
CEU DAILY PERFORMANCE DATA

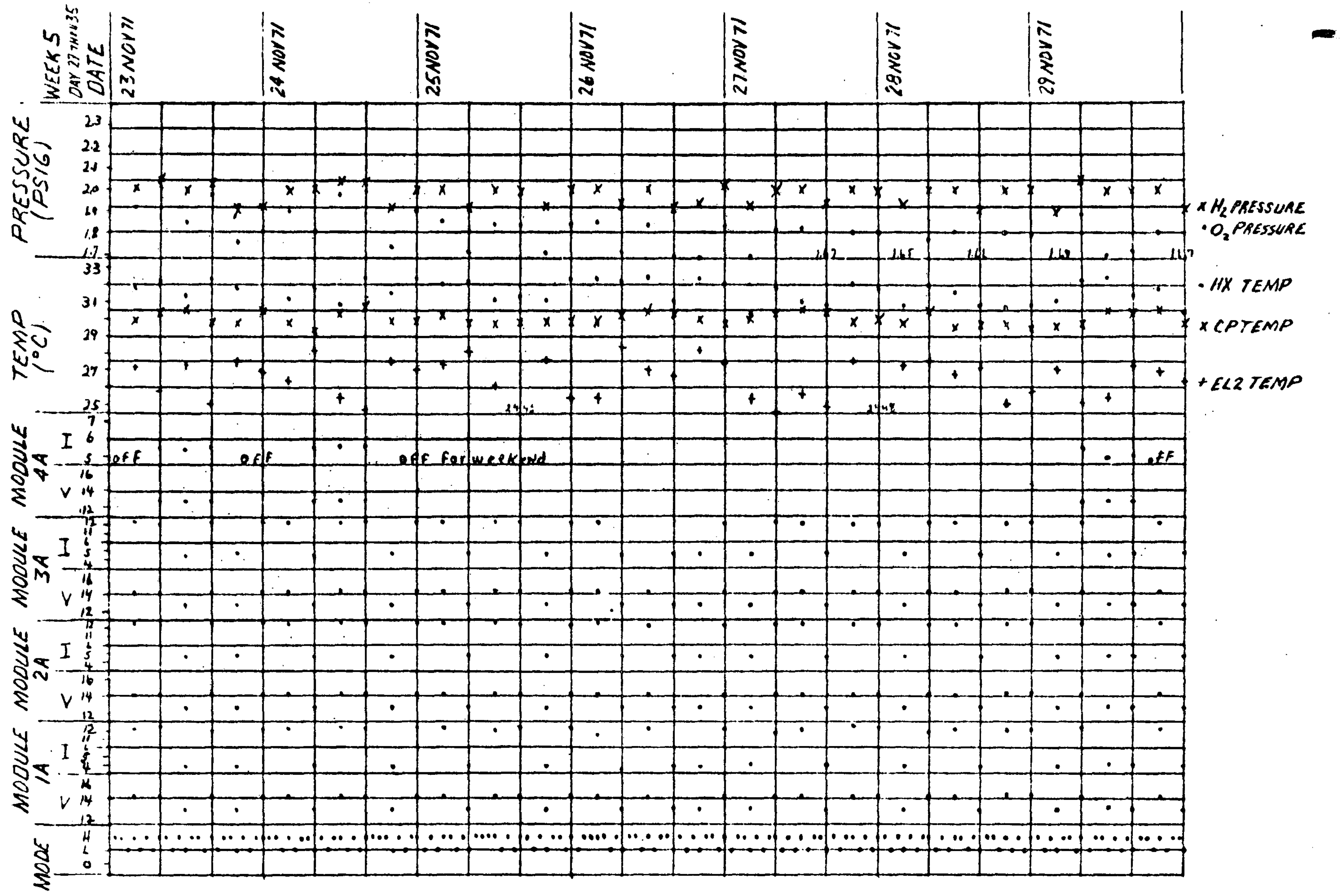

FIGURE 4-25
CEU DAILY PERFORMANCE DATA

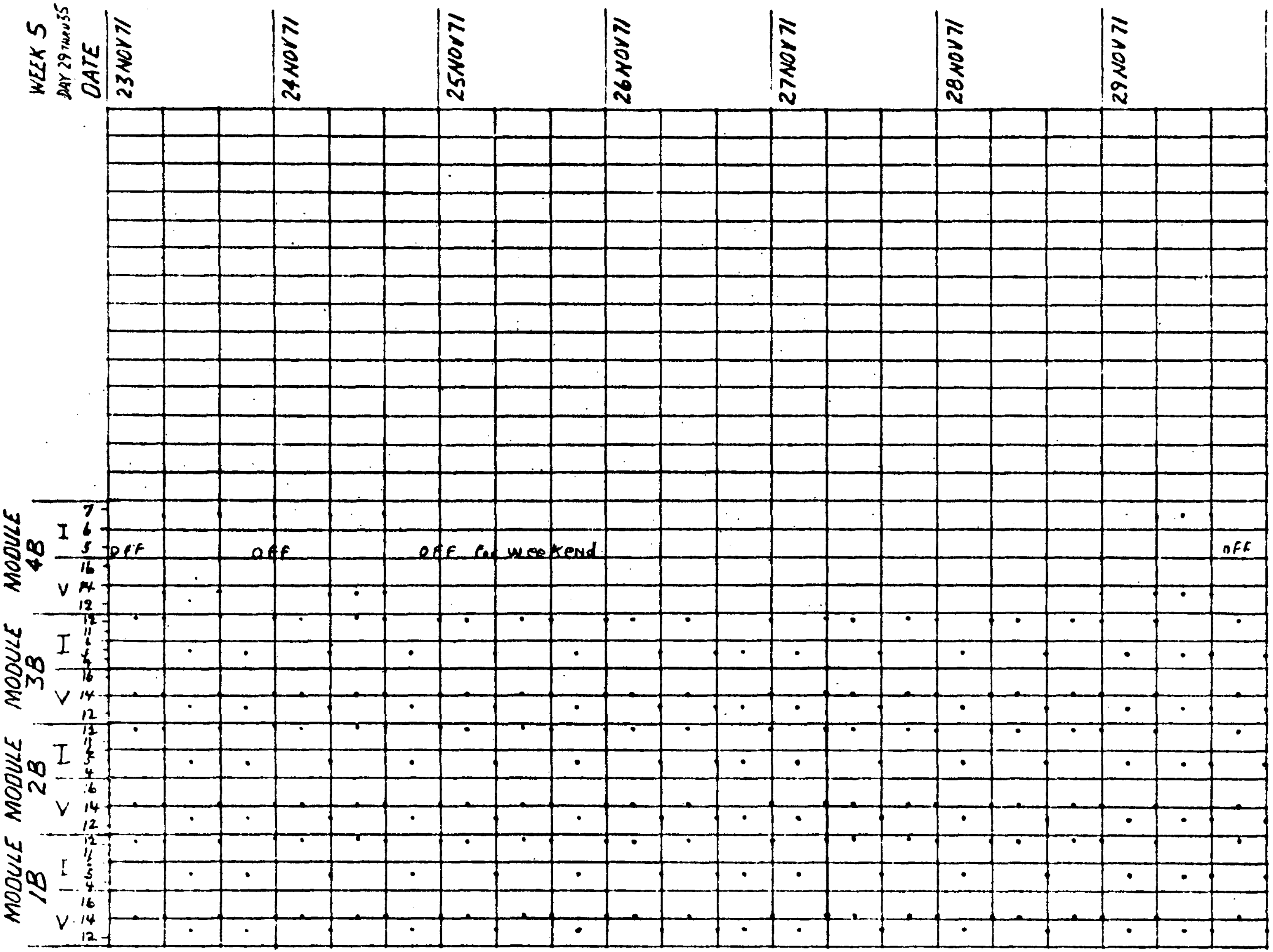

FIGURE 4-26
CELL DAILY PERFORMANCE DATA

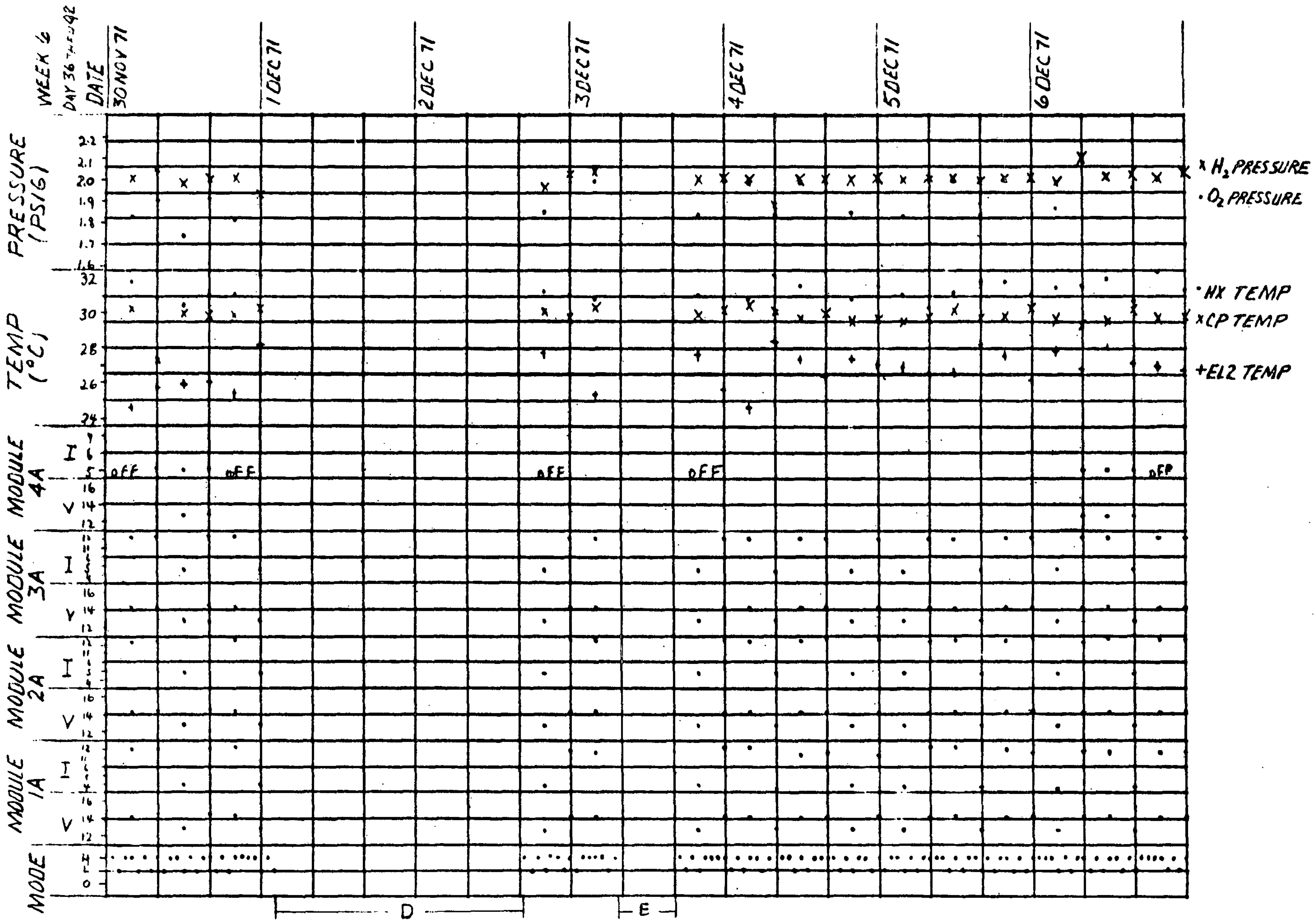

FIGURE 4-27
CEU DAILY PERFORMANCE DATA

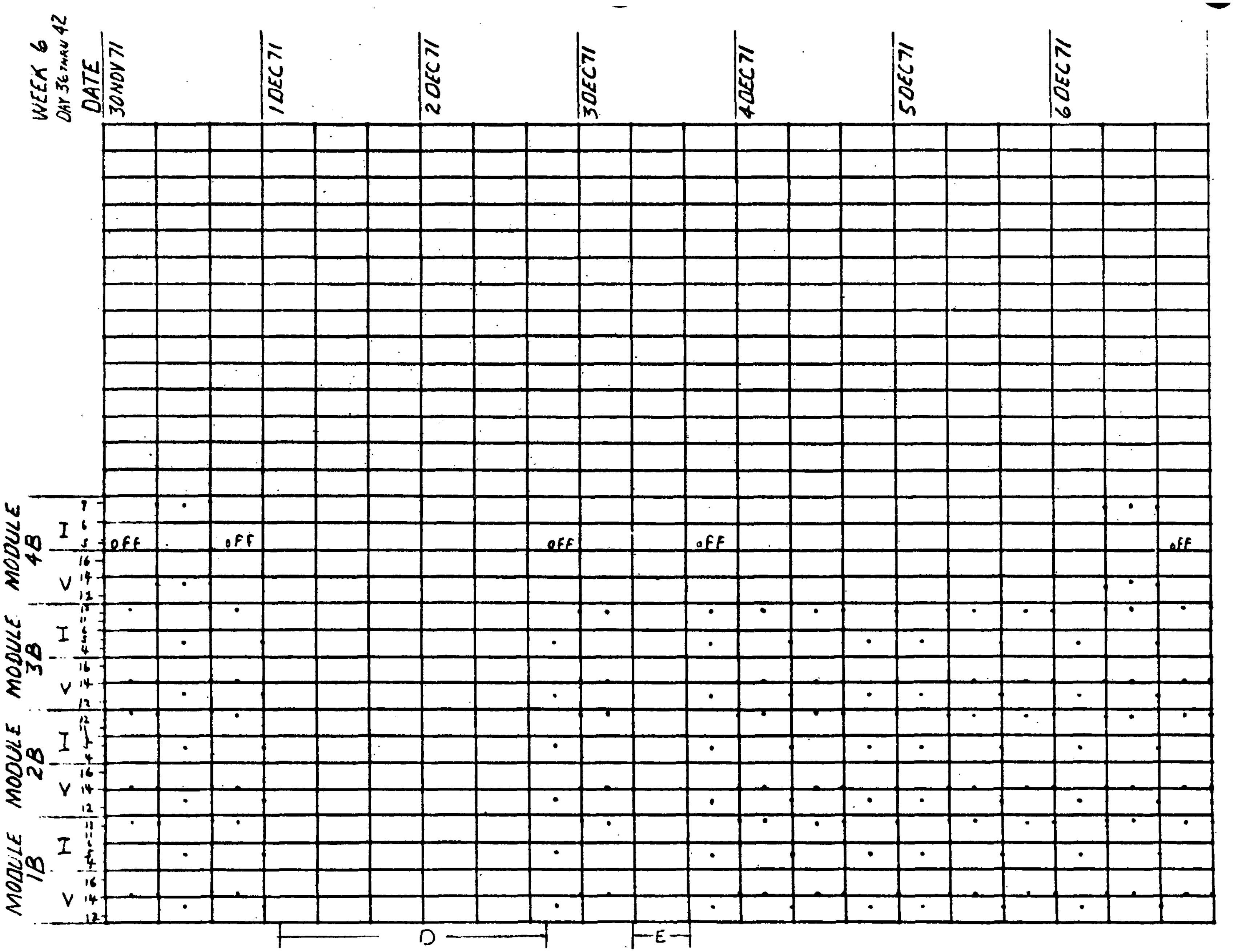

FIGURE 4-28
CEU DAILY PERFORMANCE DATA

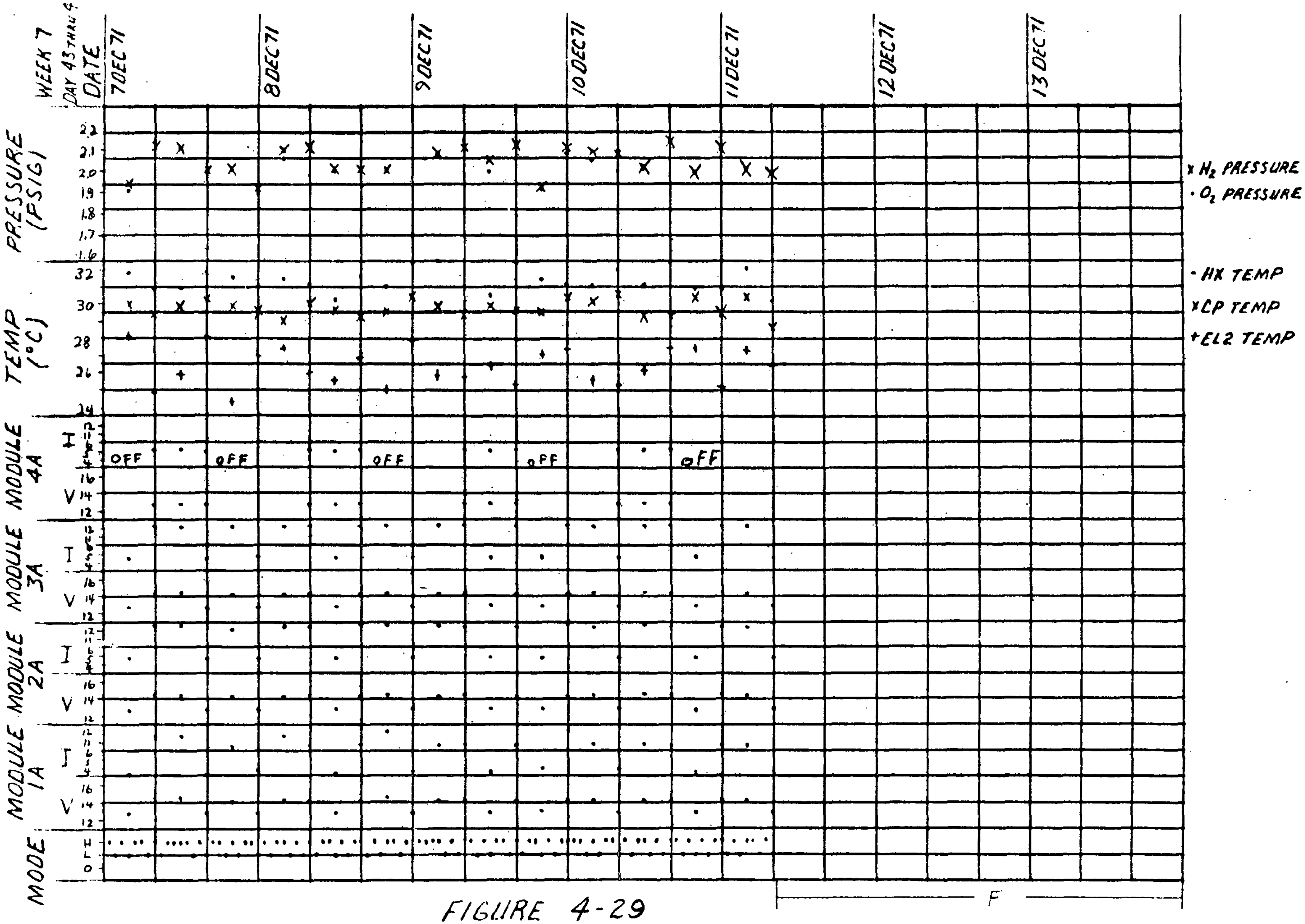

FIGURE 4-29

CEU DAILY PERFORMANCE DATA

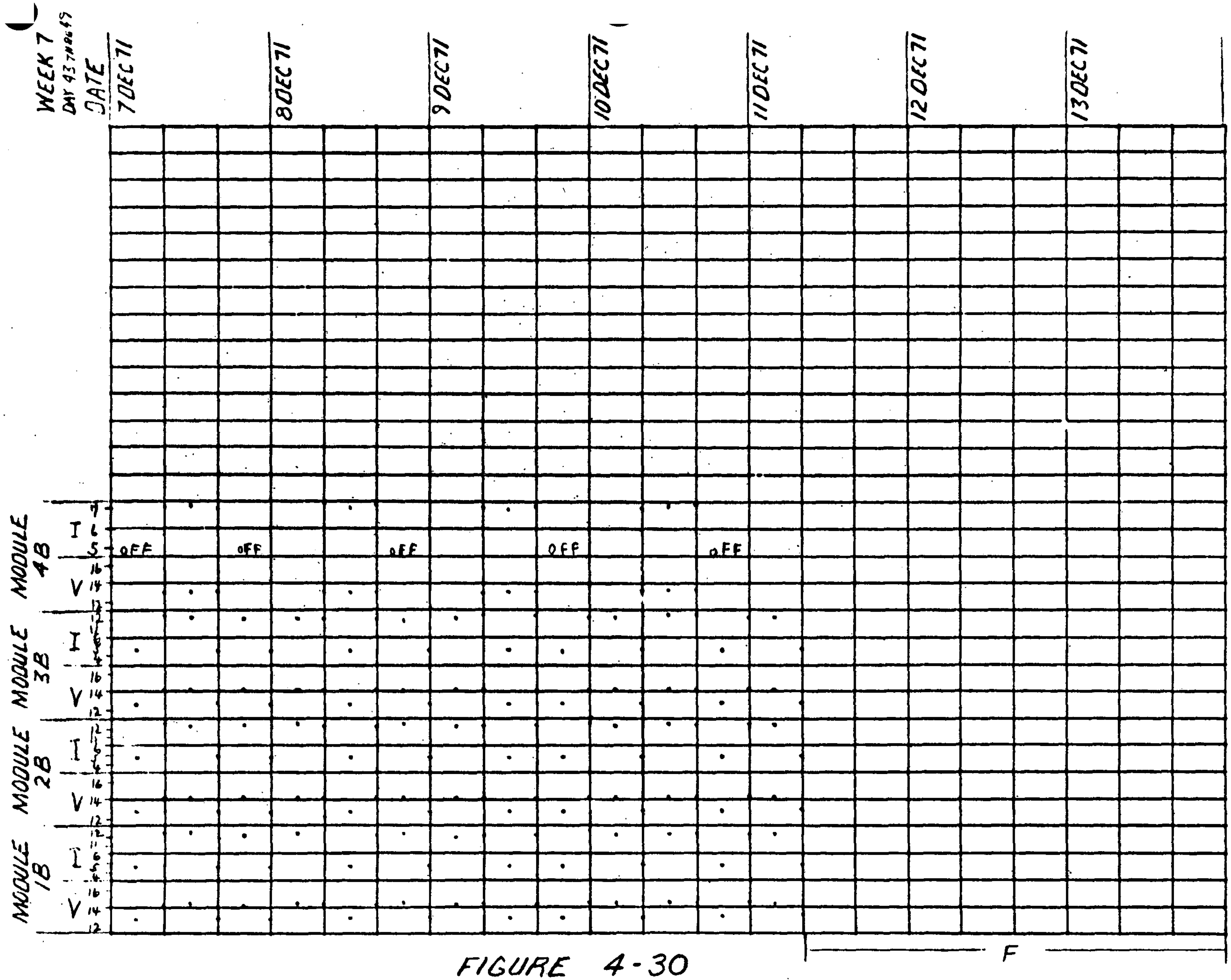

FIGURE 4-30
CEU DAILY PERFORMANCE DATA

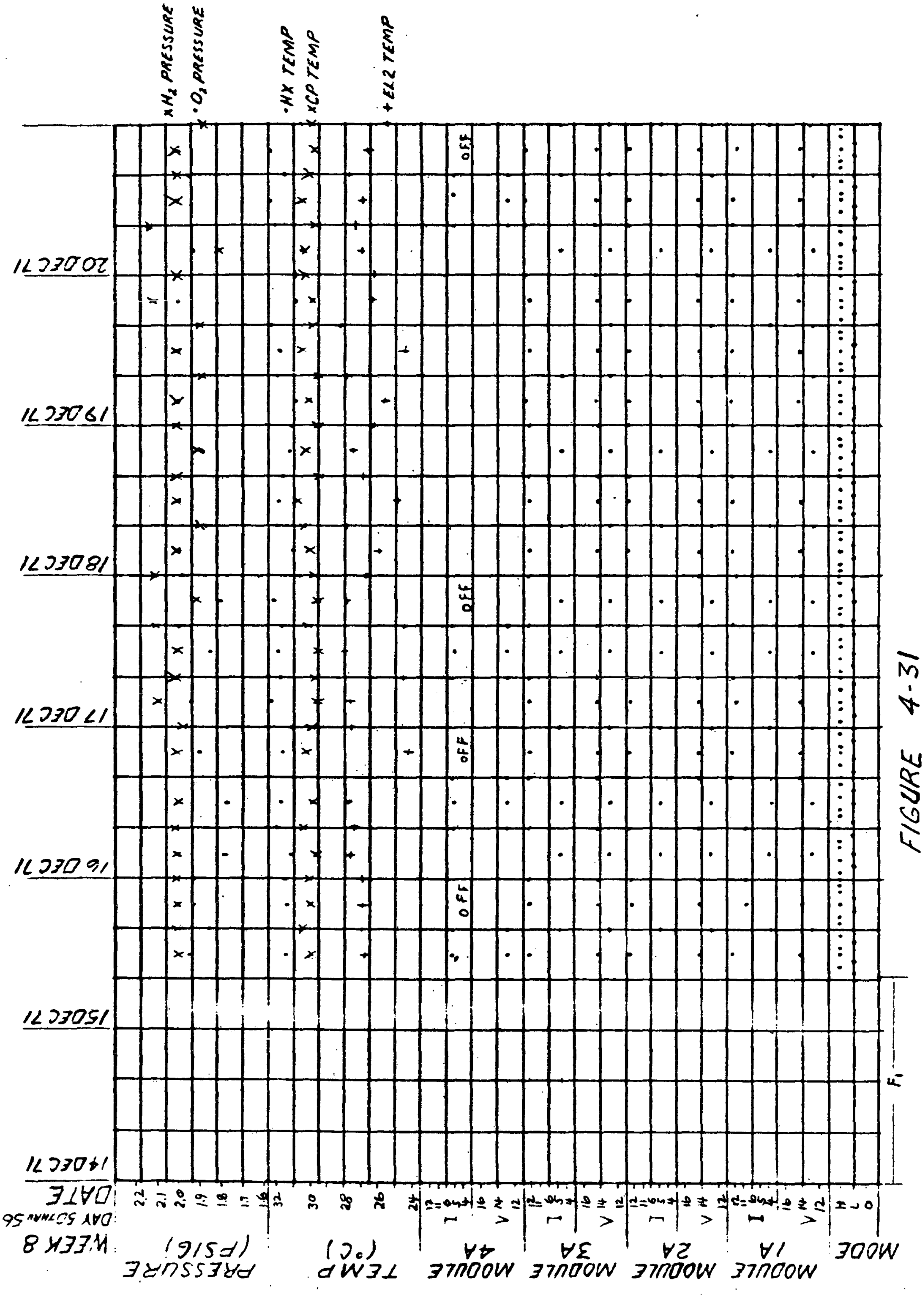

FIGURE 4-31
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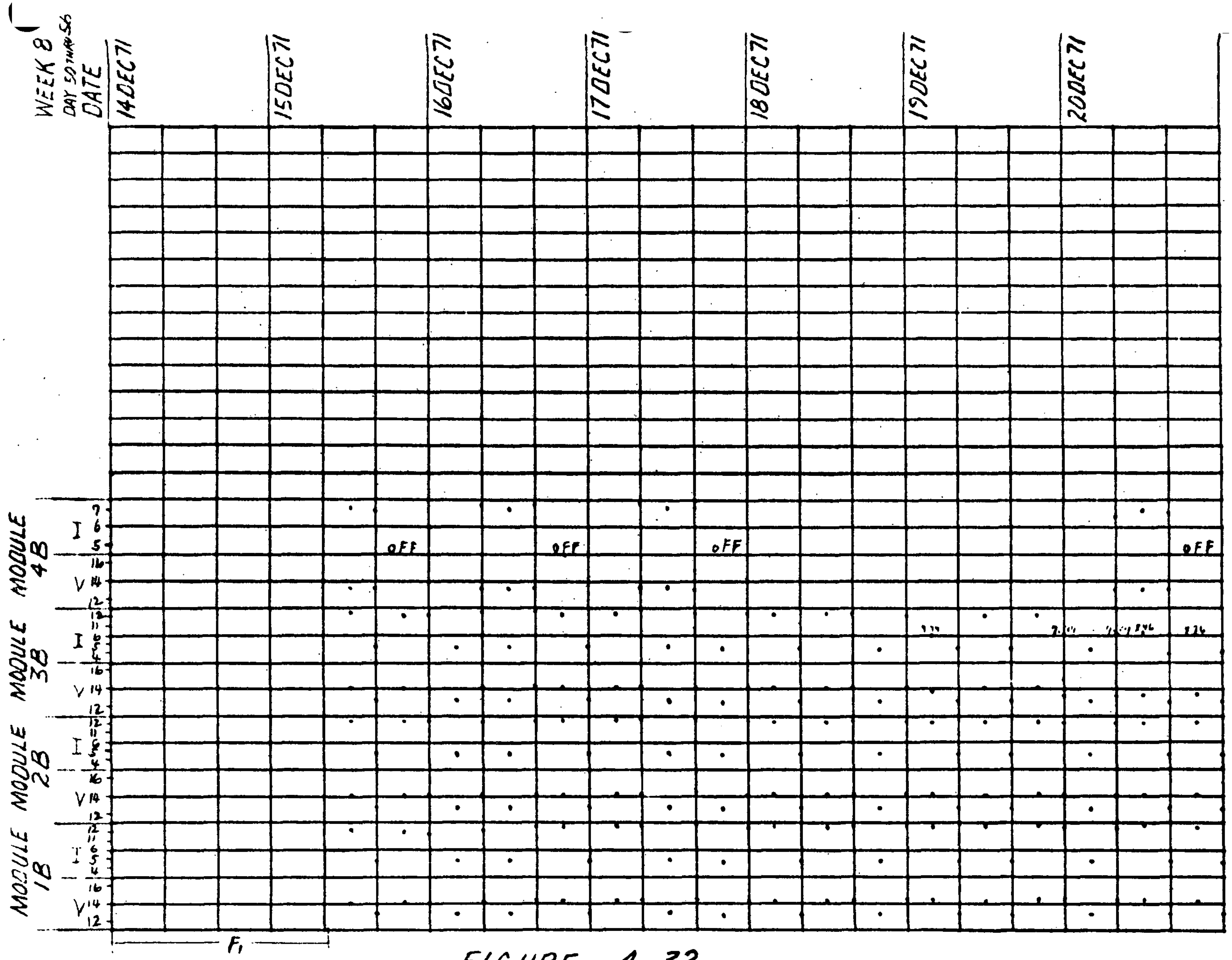

FIGURE 4-32
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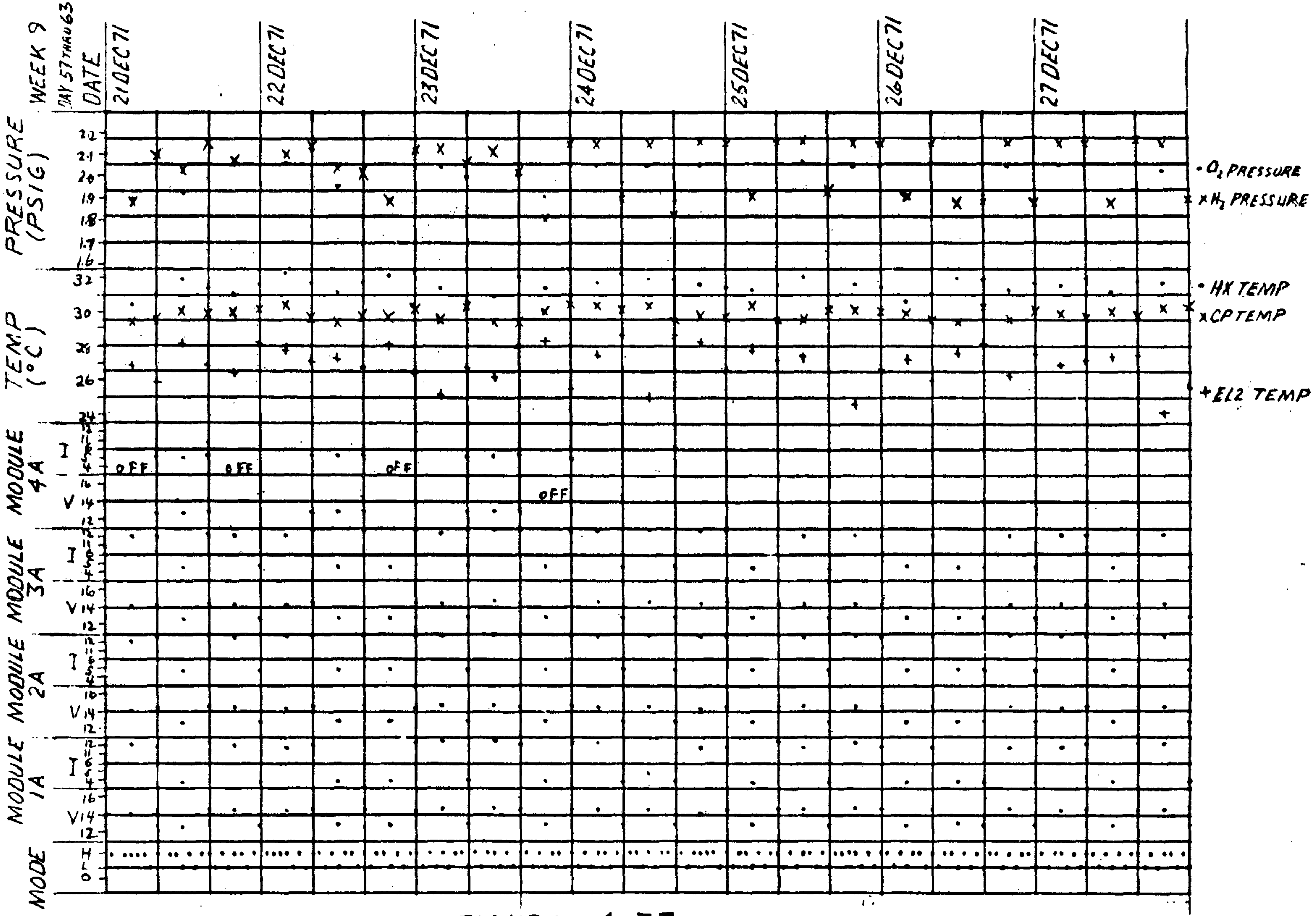

FIGURE 4-33
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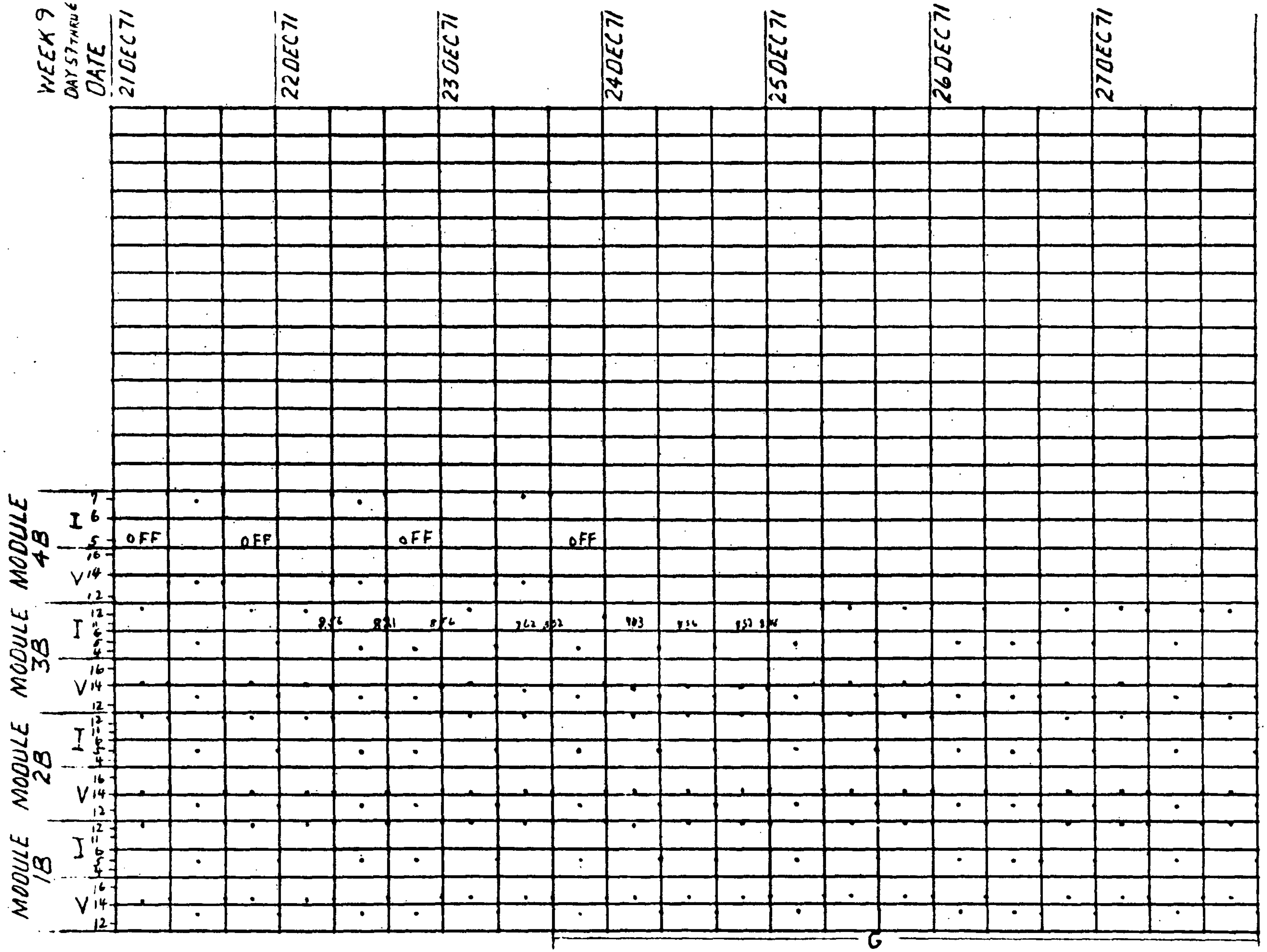

FIGURE 4-34

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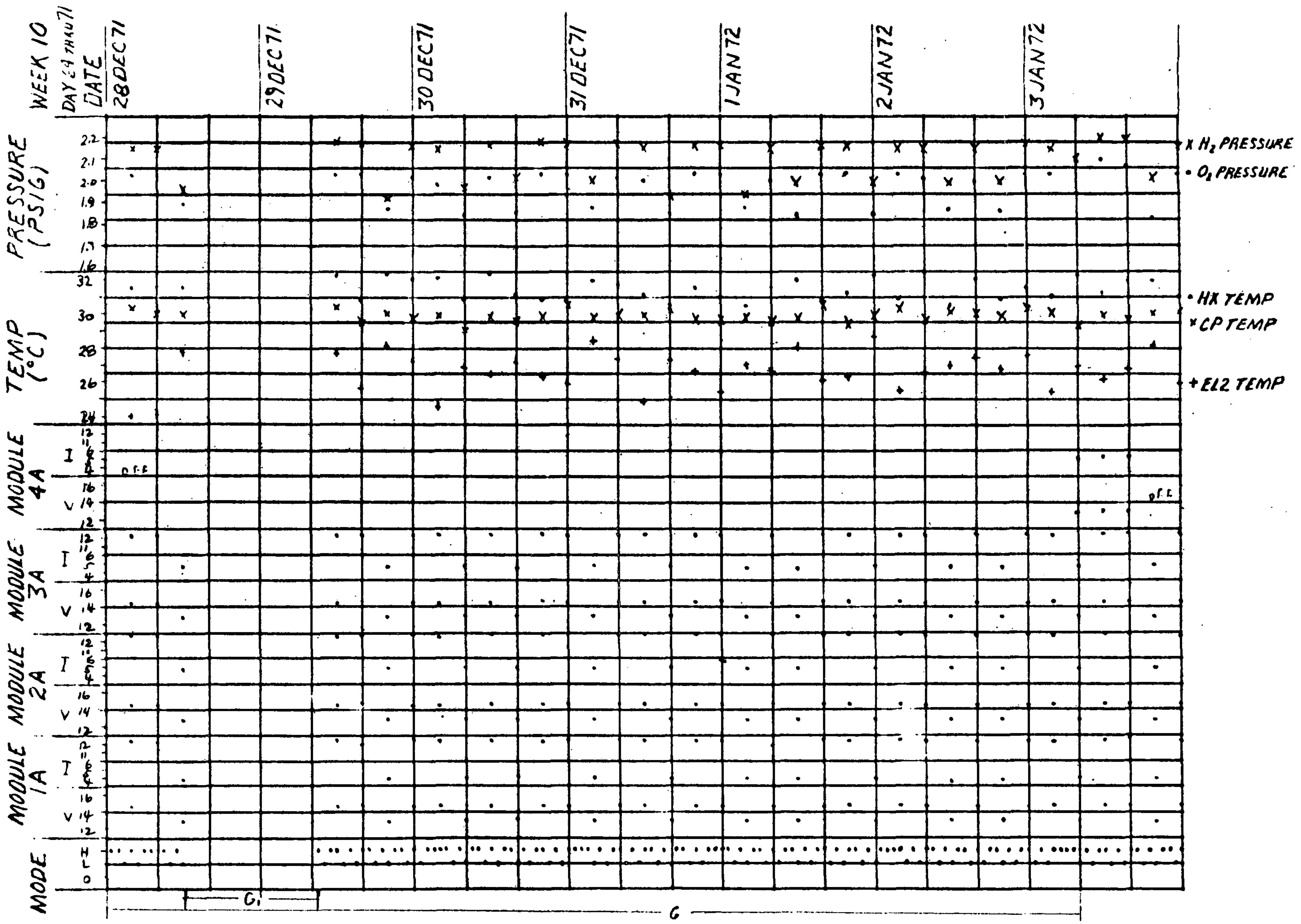

FIGURE 4-35

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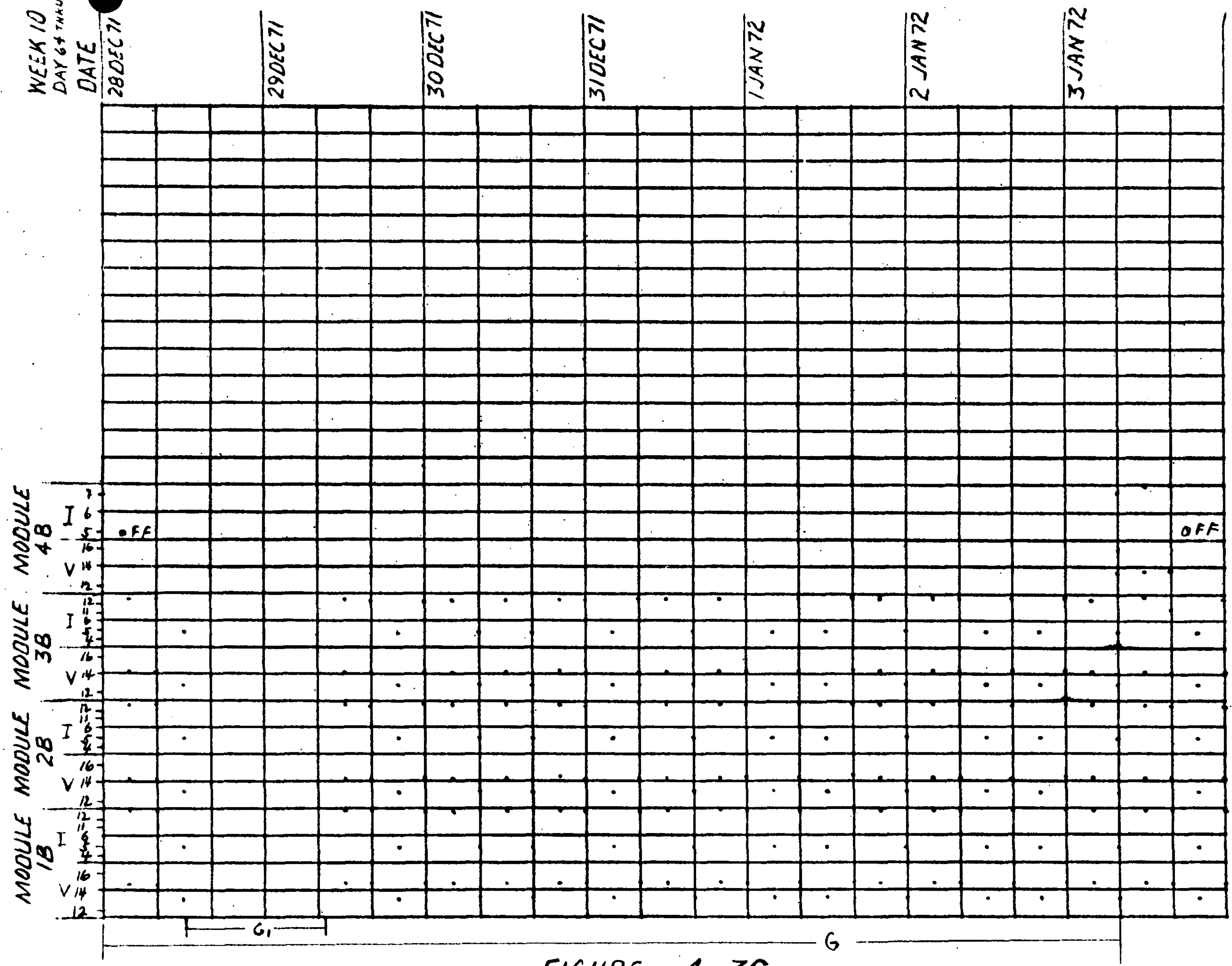

FIGURE 4-36

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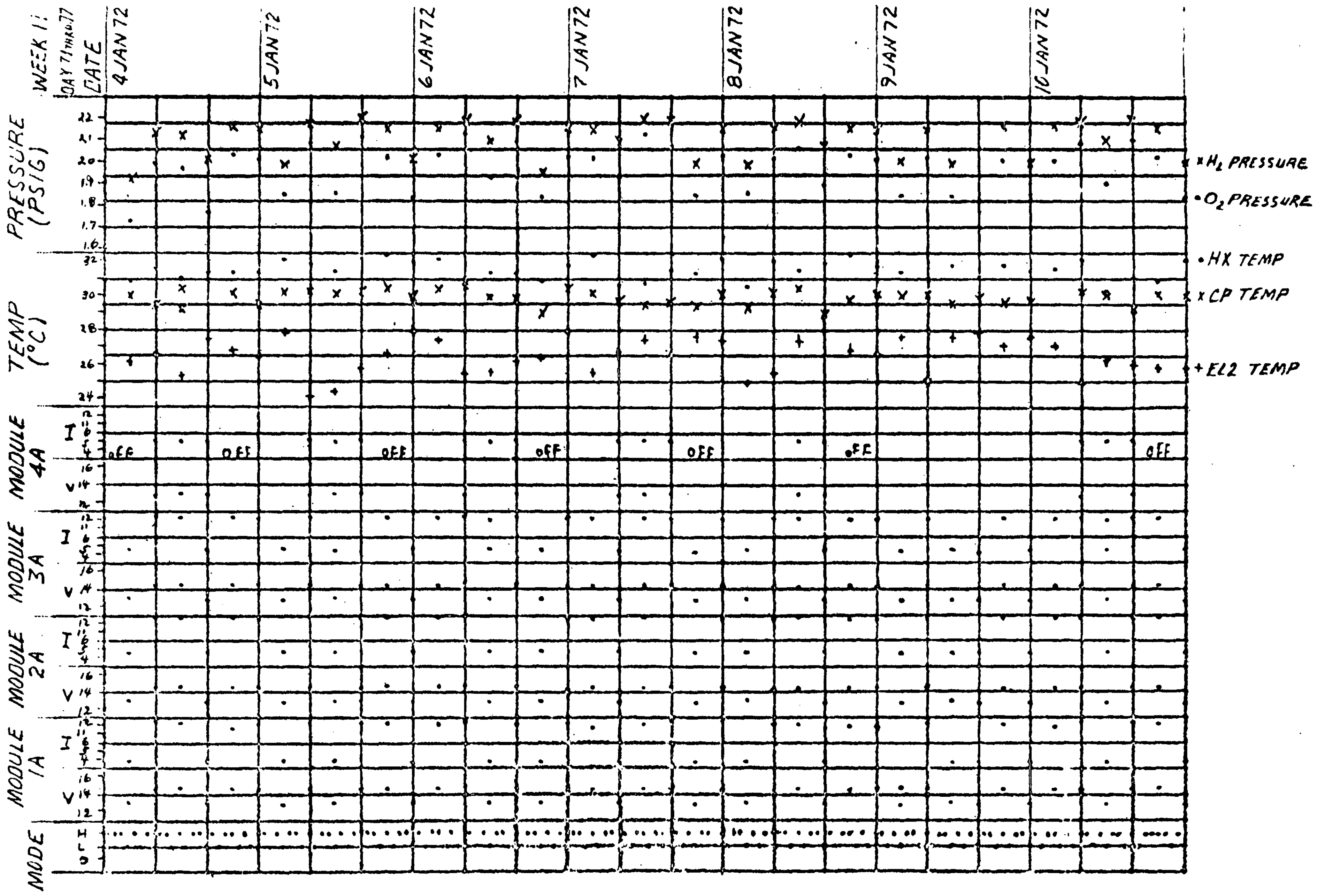

FIGURE 4-37
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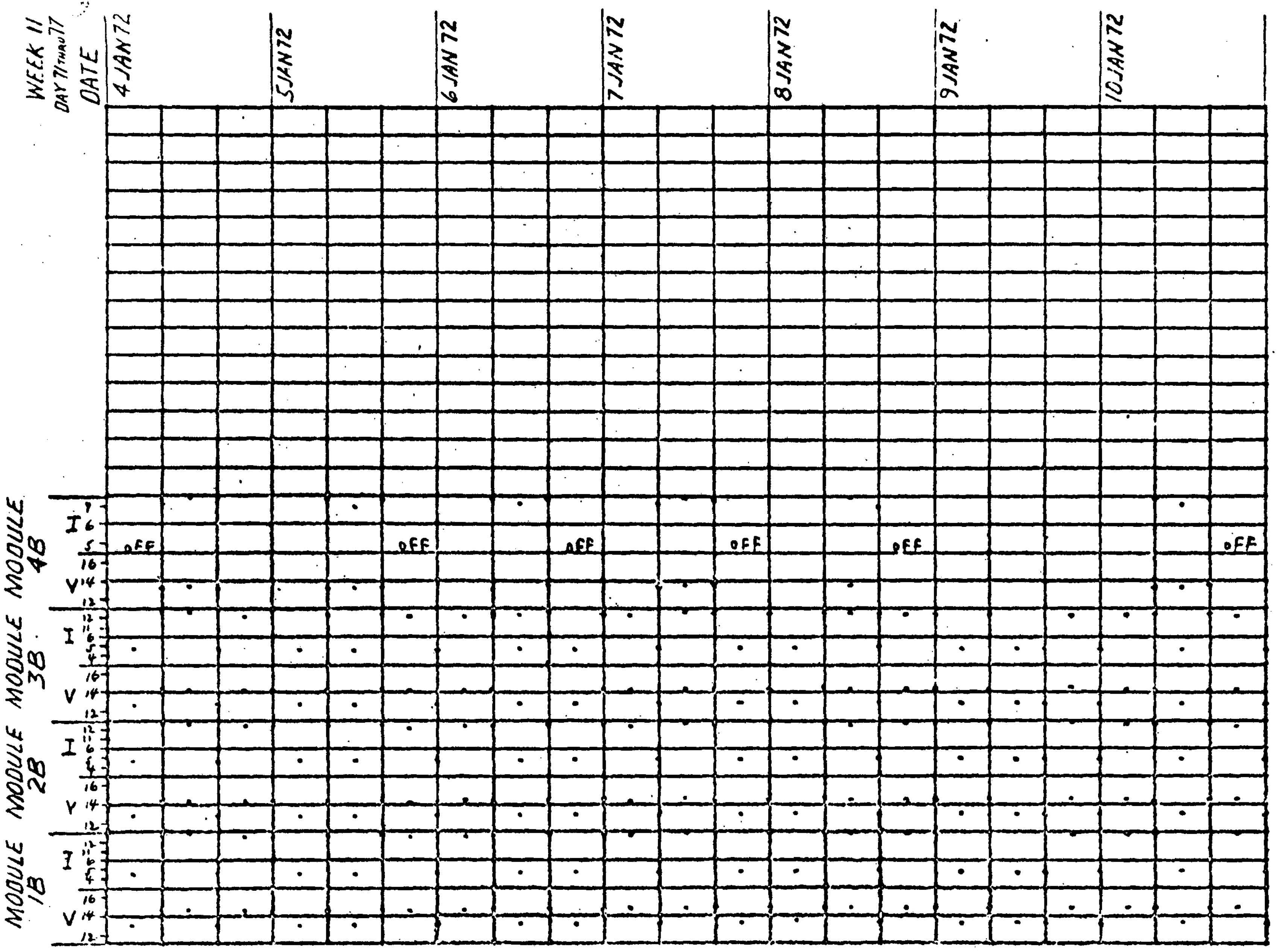

FIGURE 4-38
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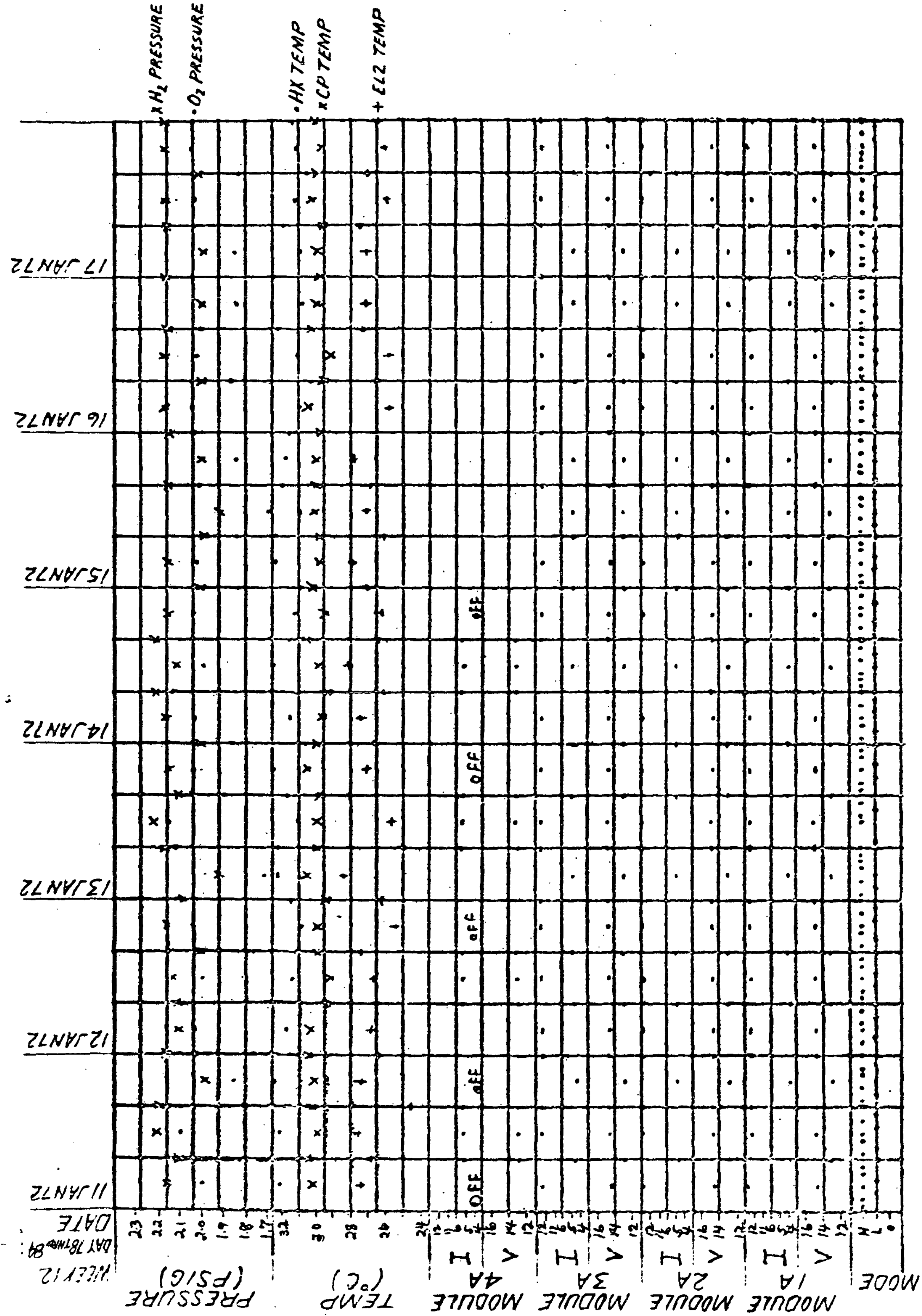

FIGURE 4-39

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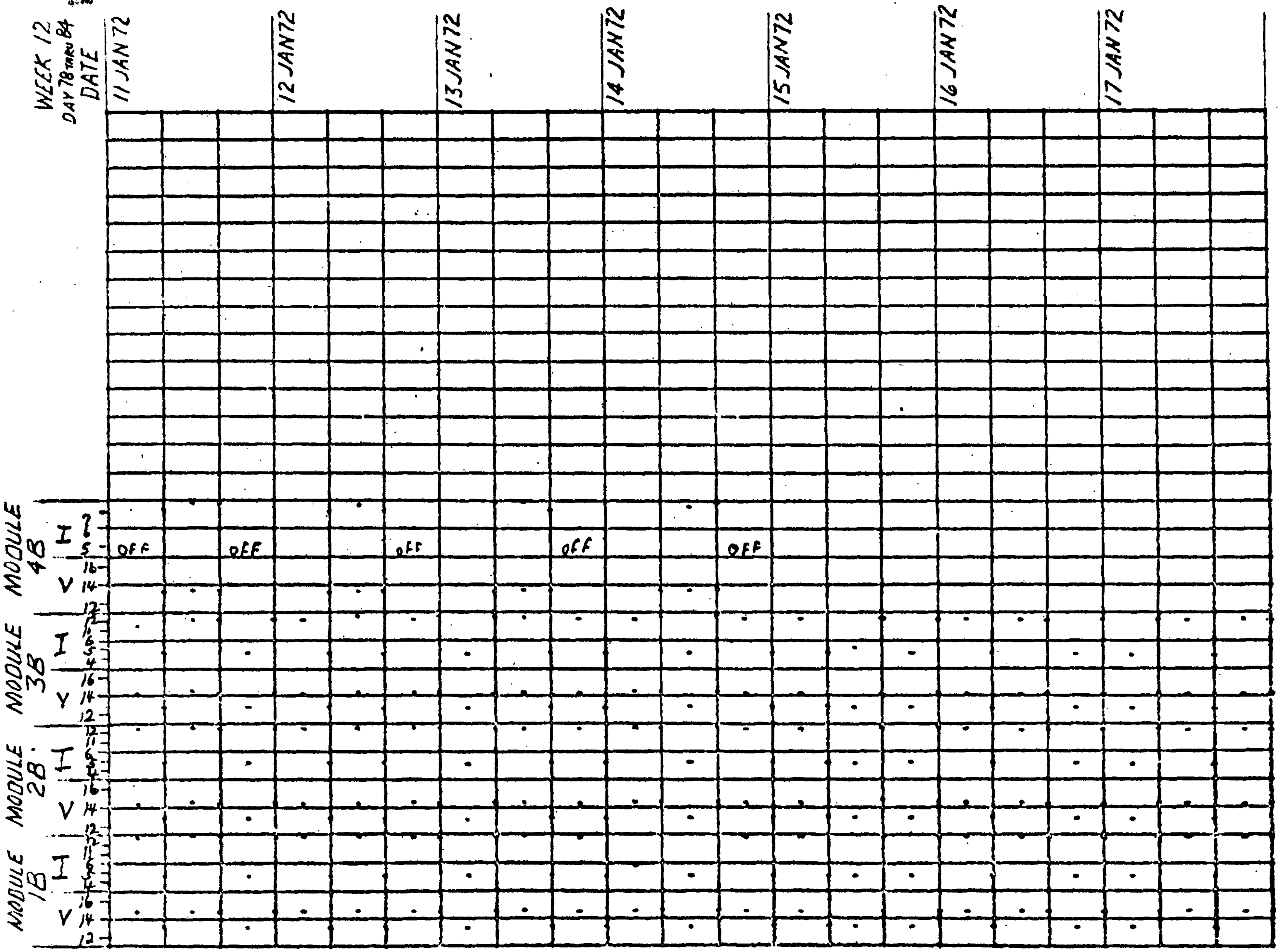

FIGURE 4-40
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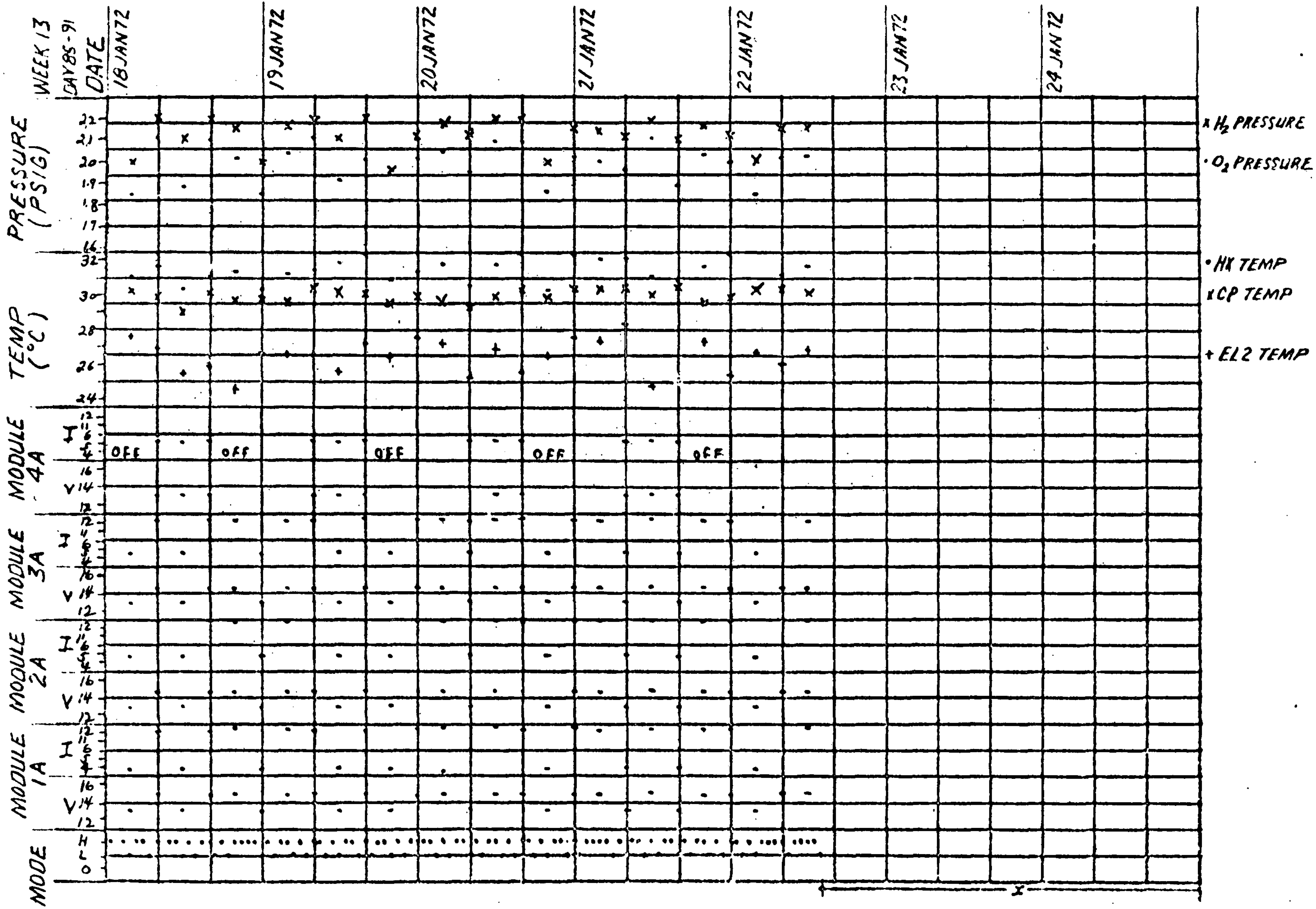

FIGURE 4-41
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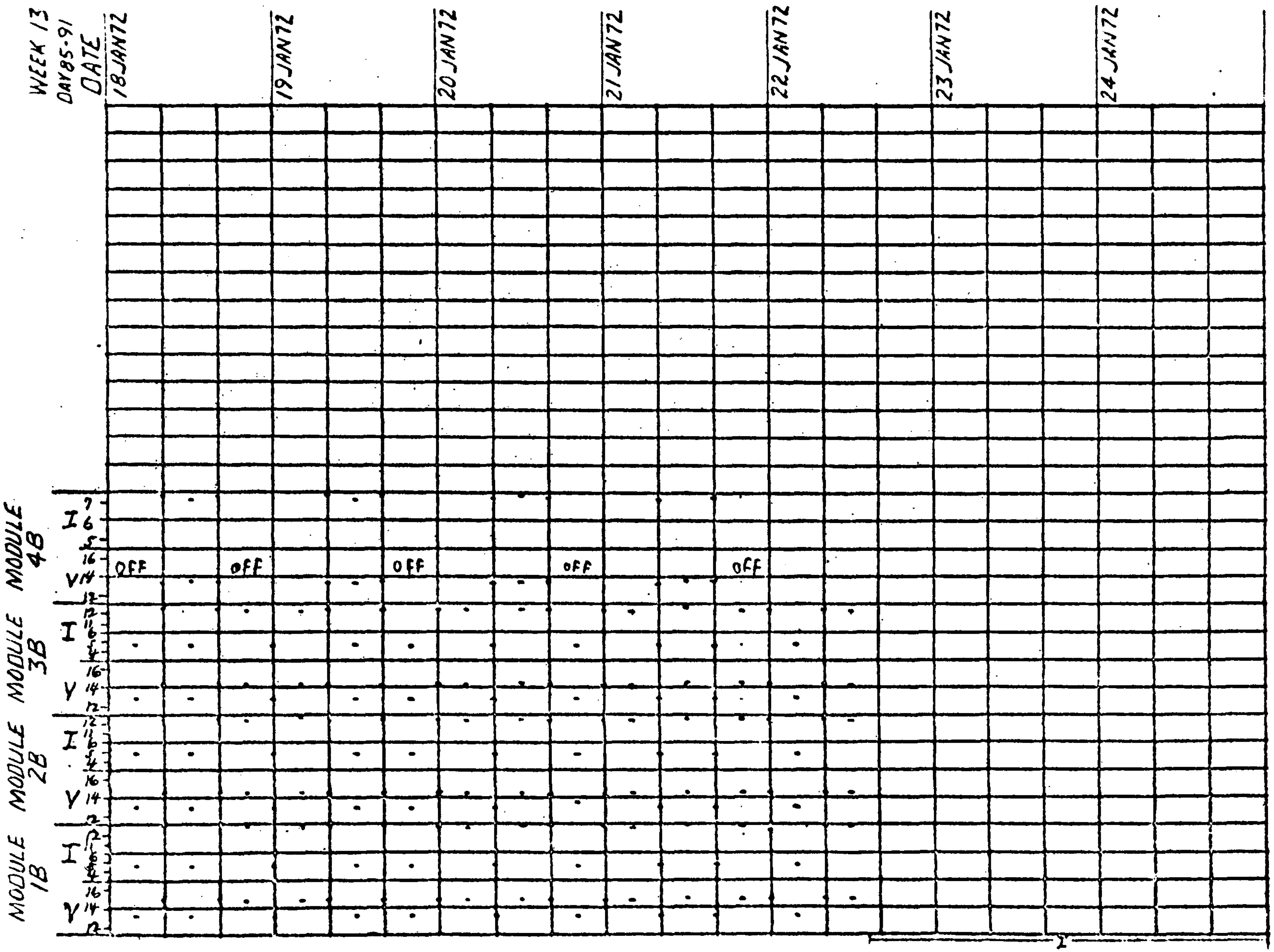

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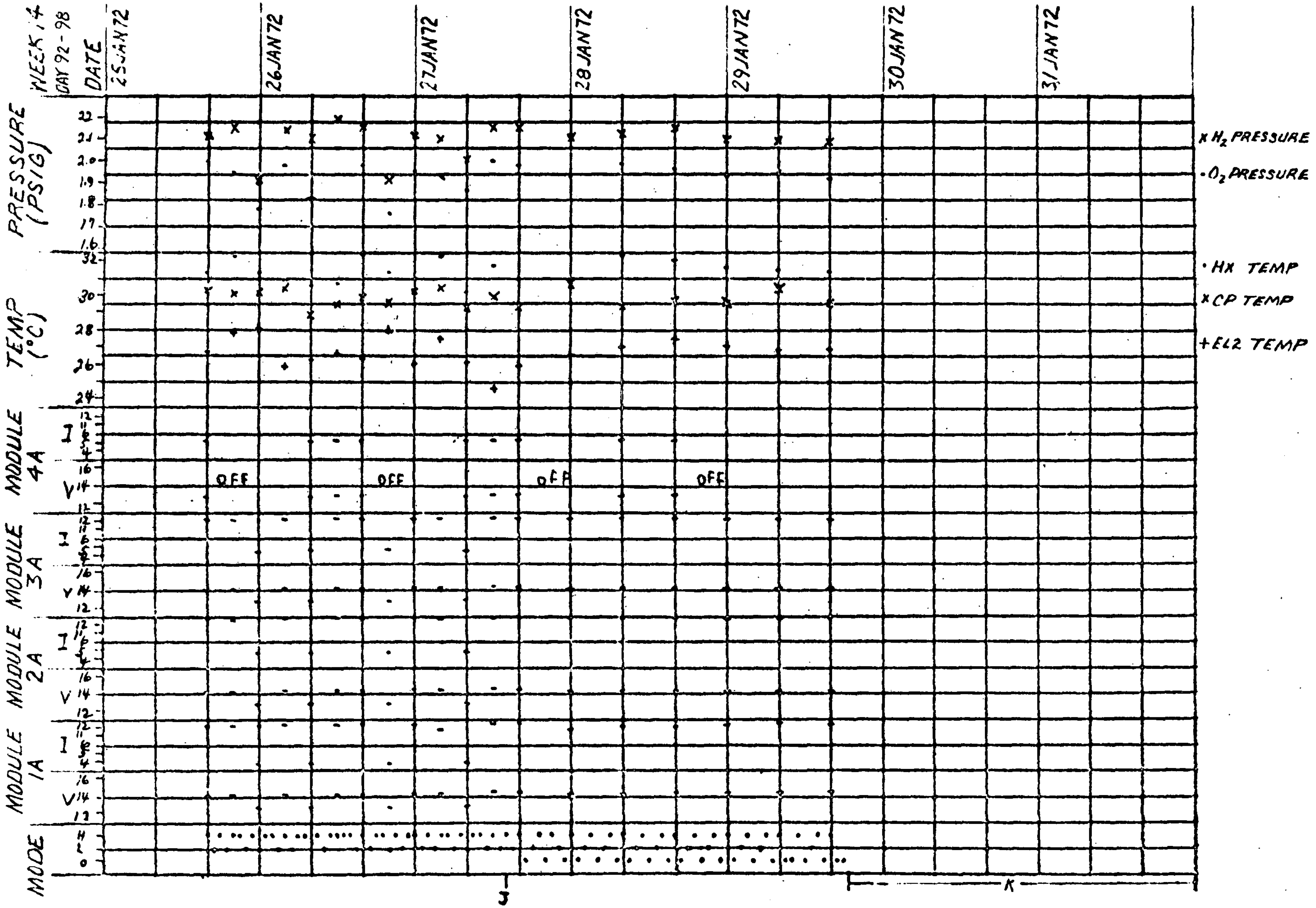

FIGURE 4-43
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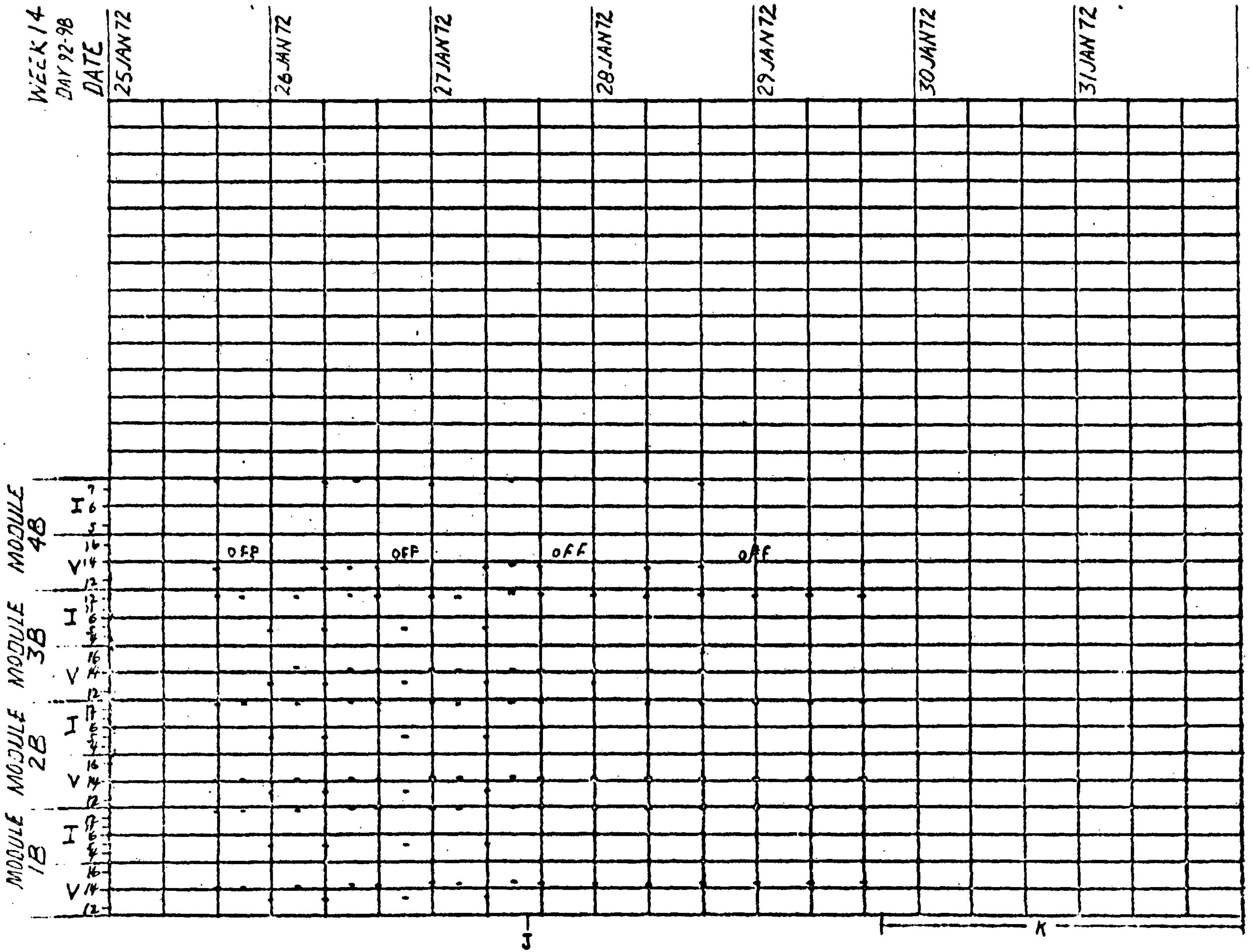

FIGURE 4-44

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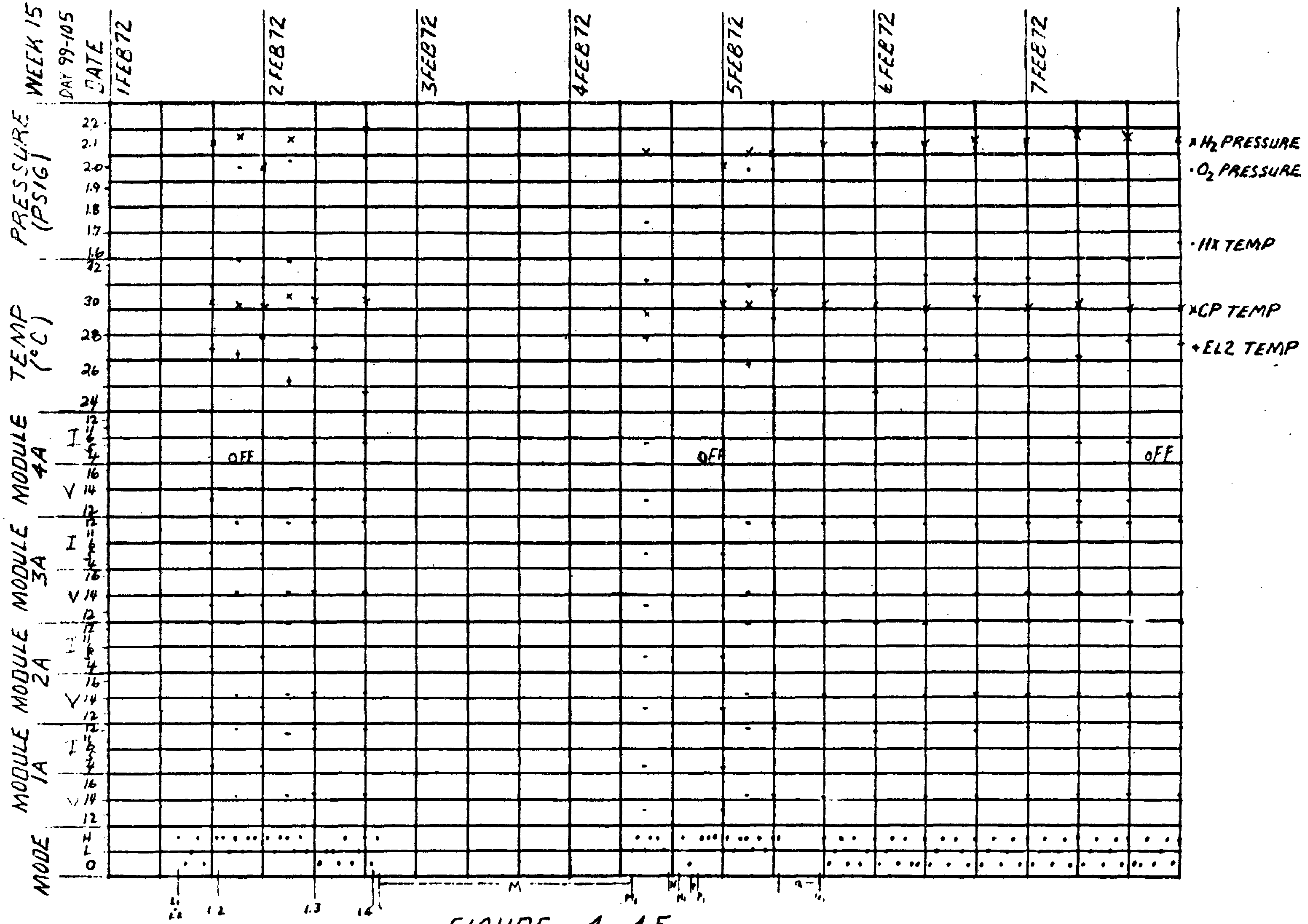

FIGURE 4-45

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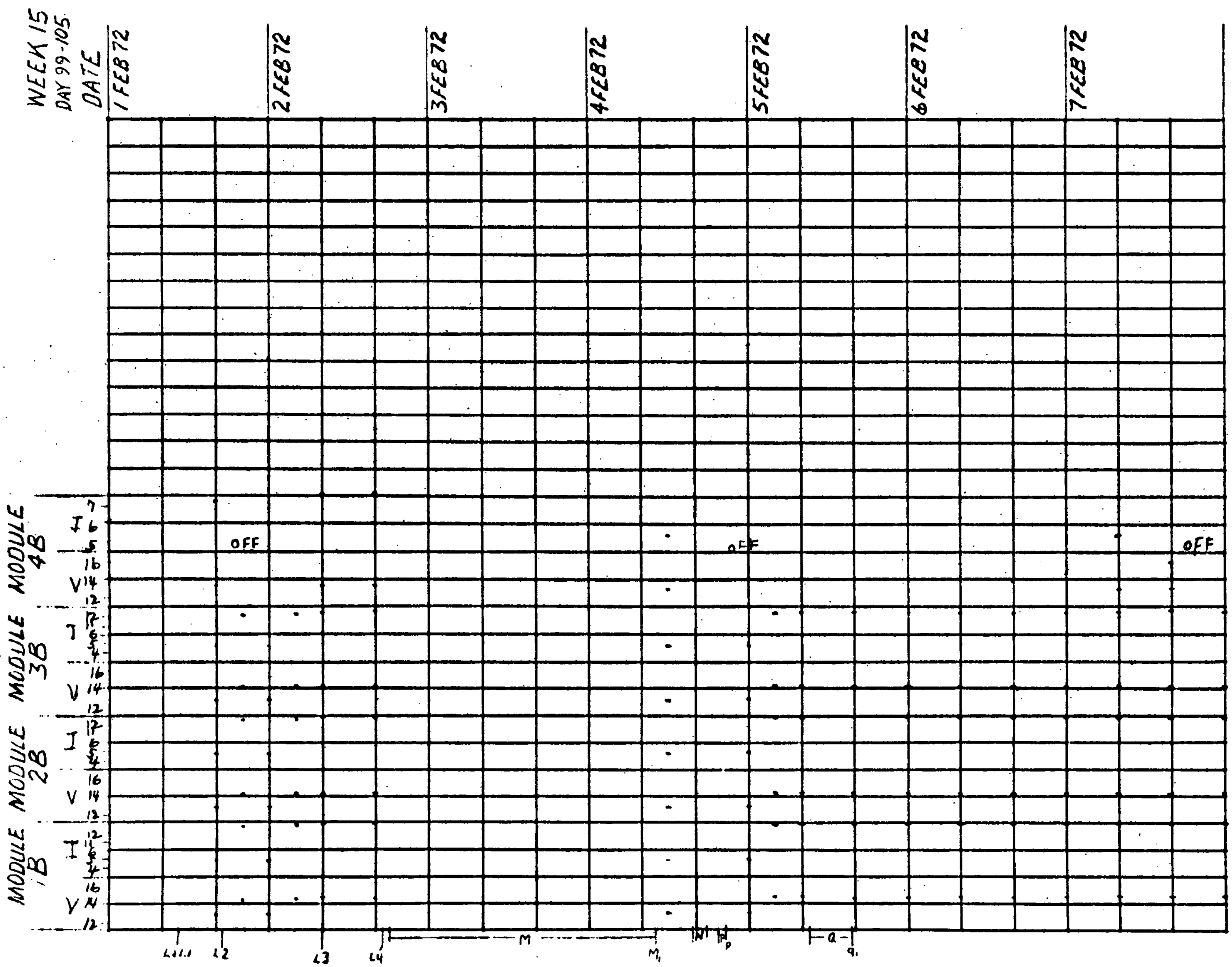

FIGURE 4-46
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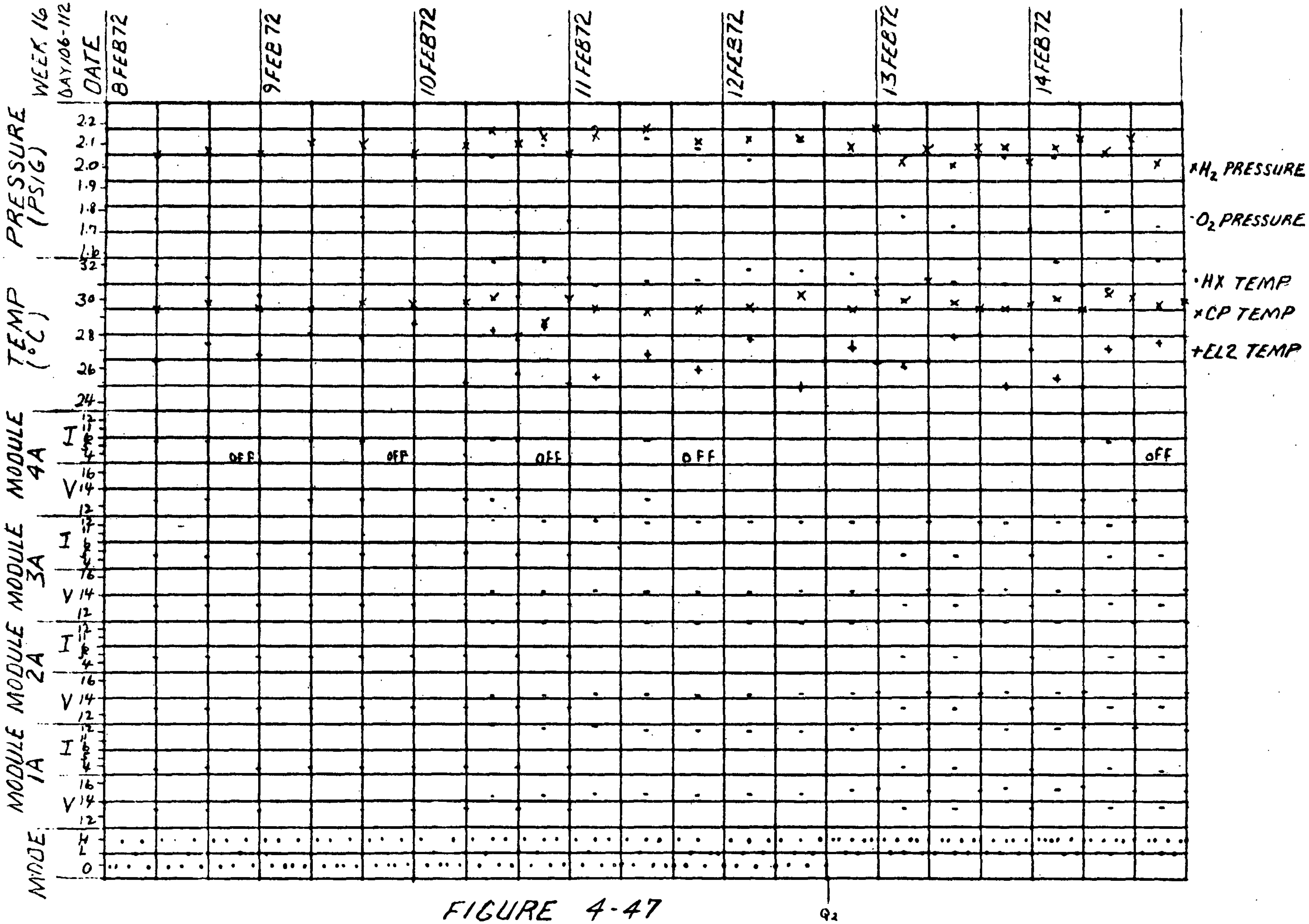

FIGURE 4-47
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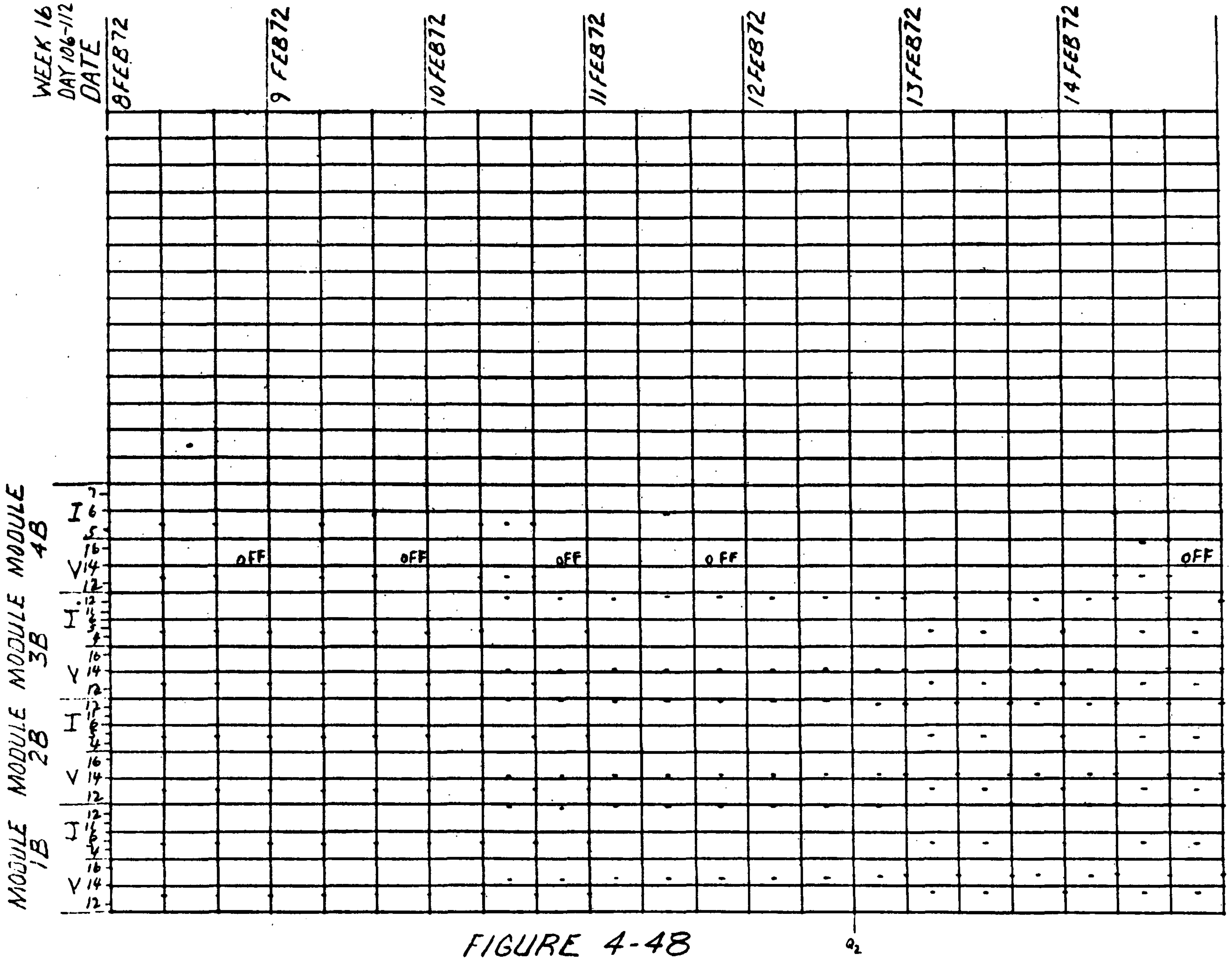

FIGURE 4-48
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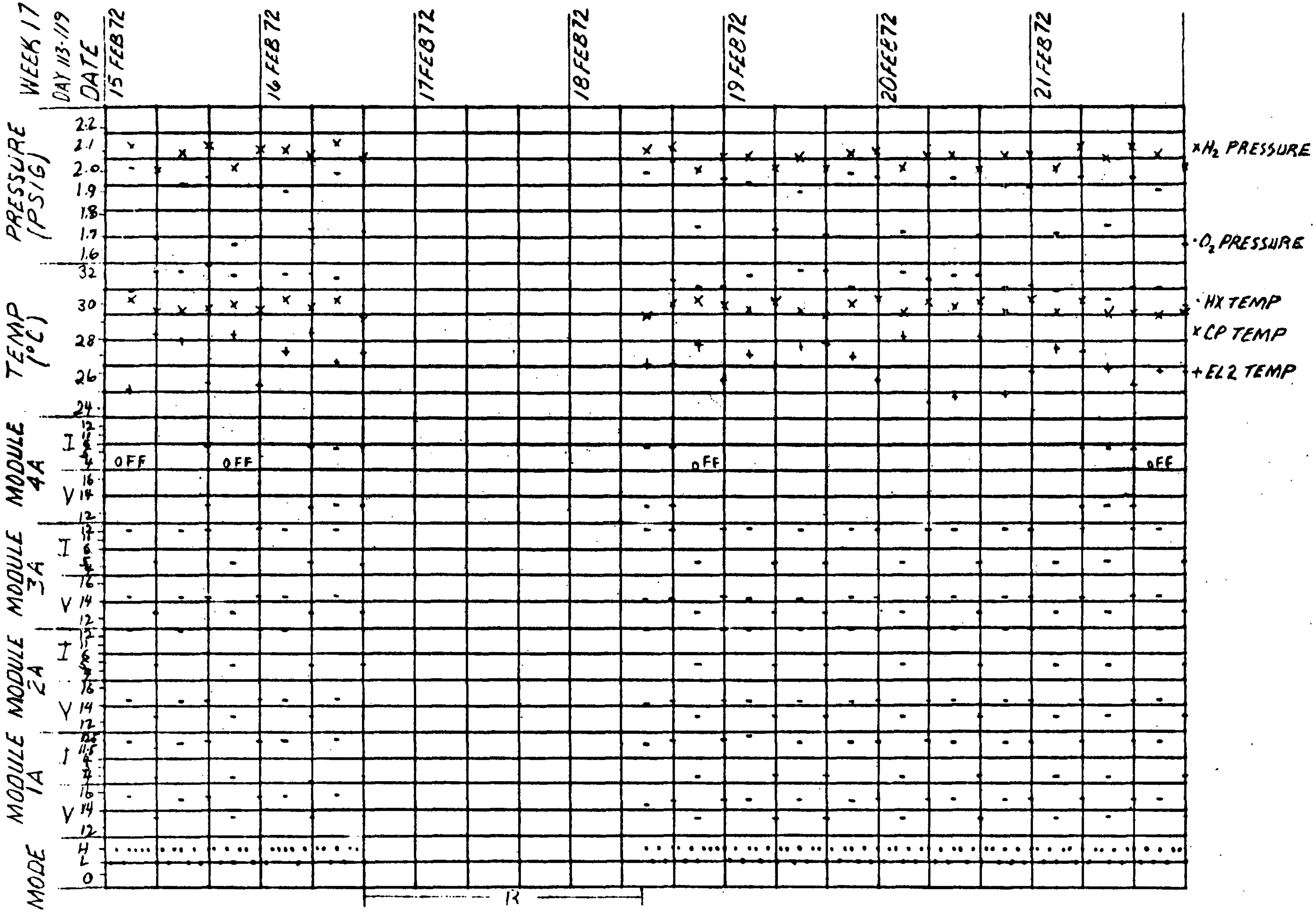

FIGURE 4-49
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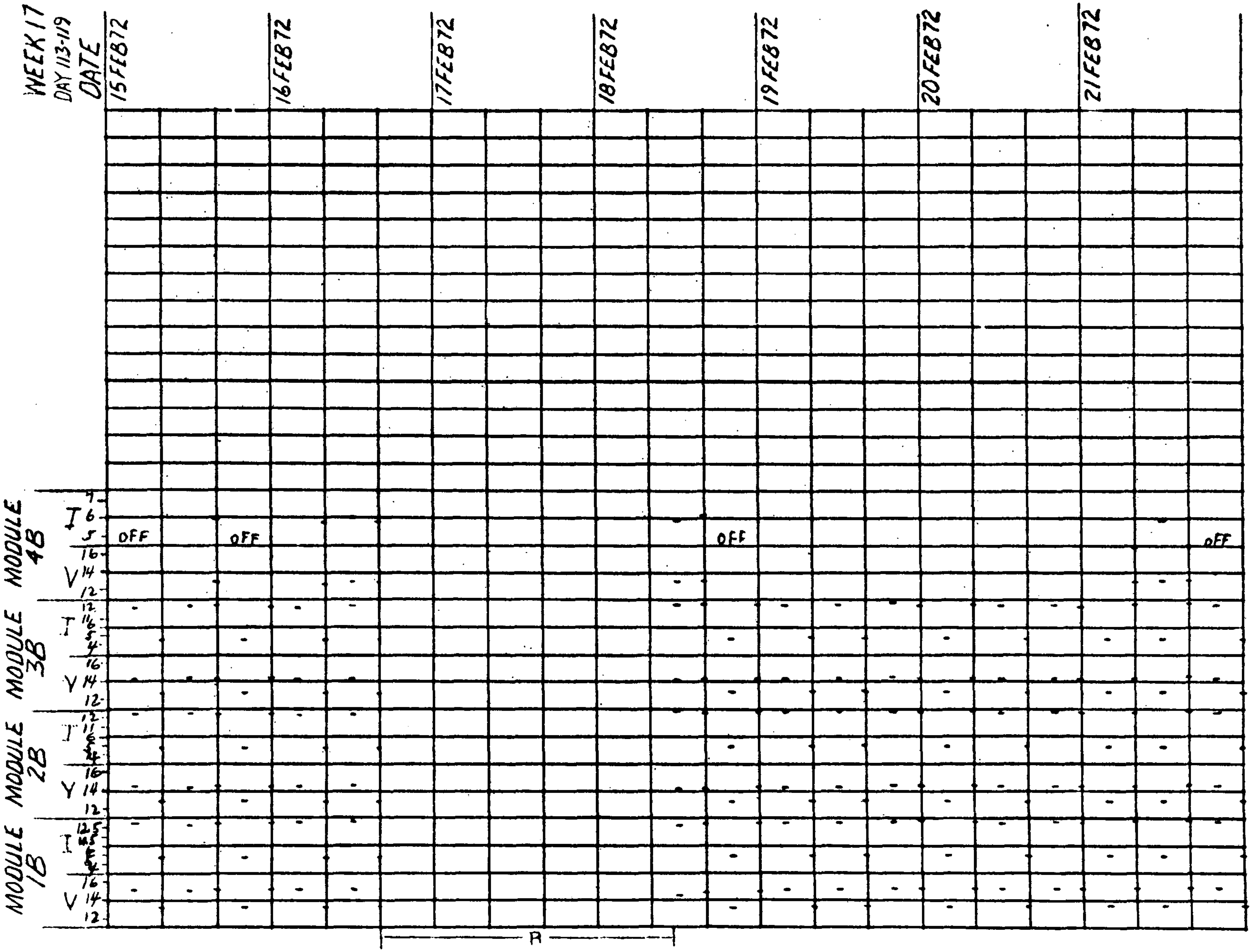

FIGURE 4-50
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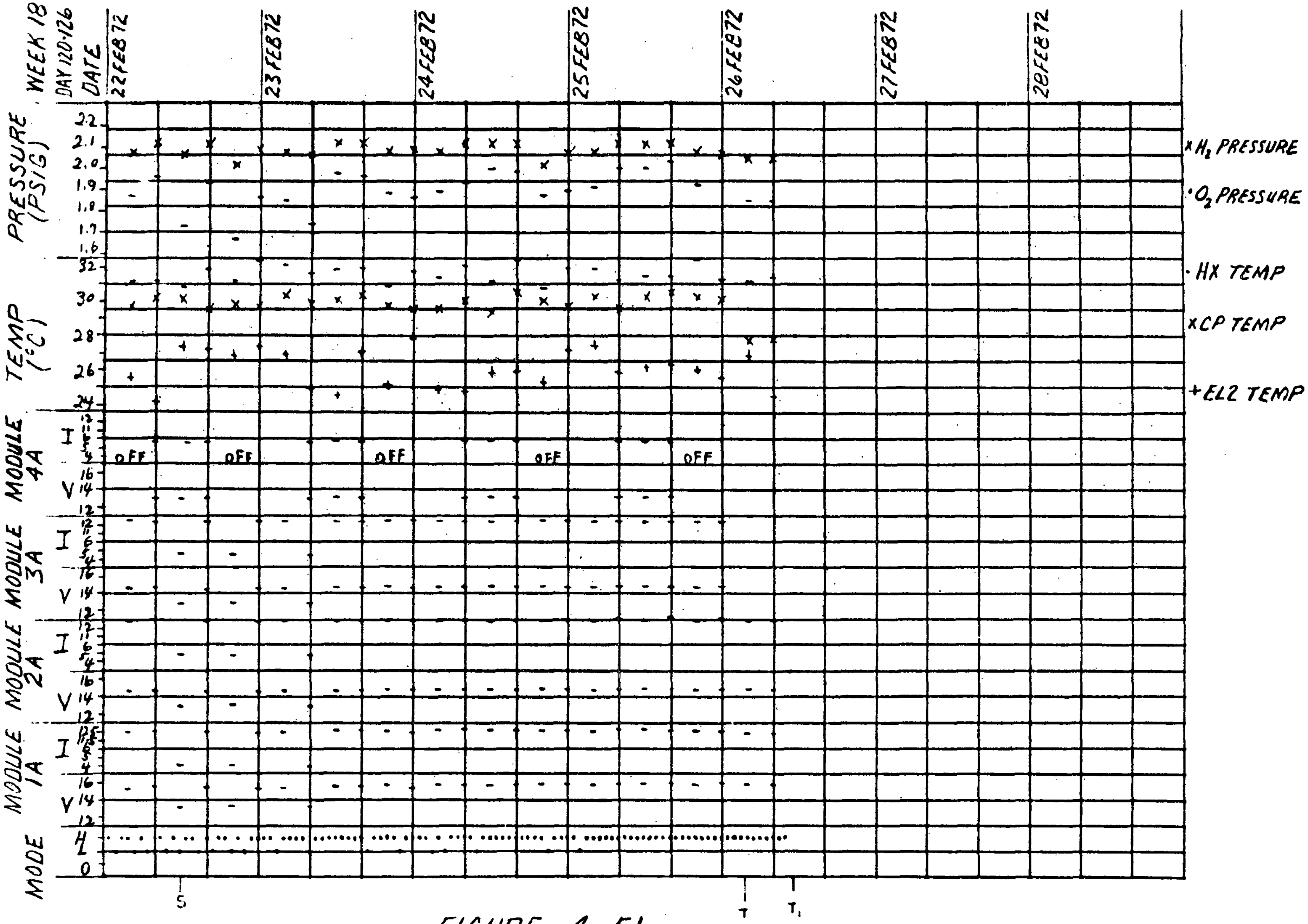

FIGURE 4-51
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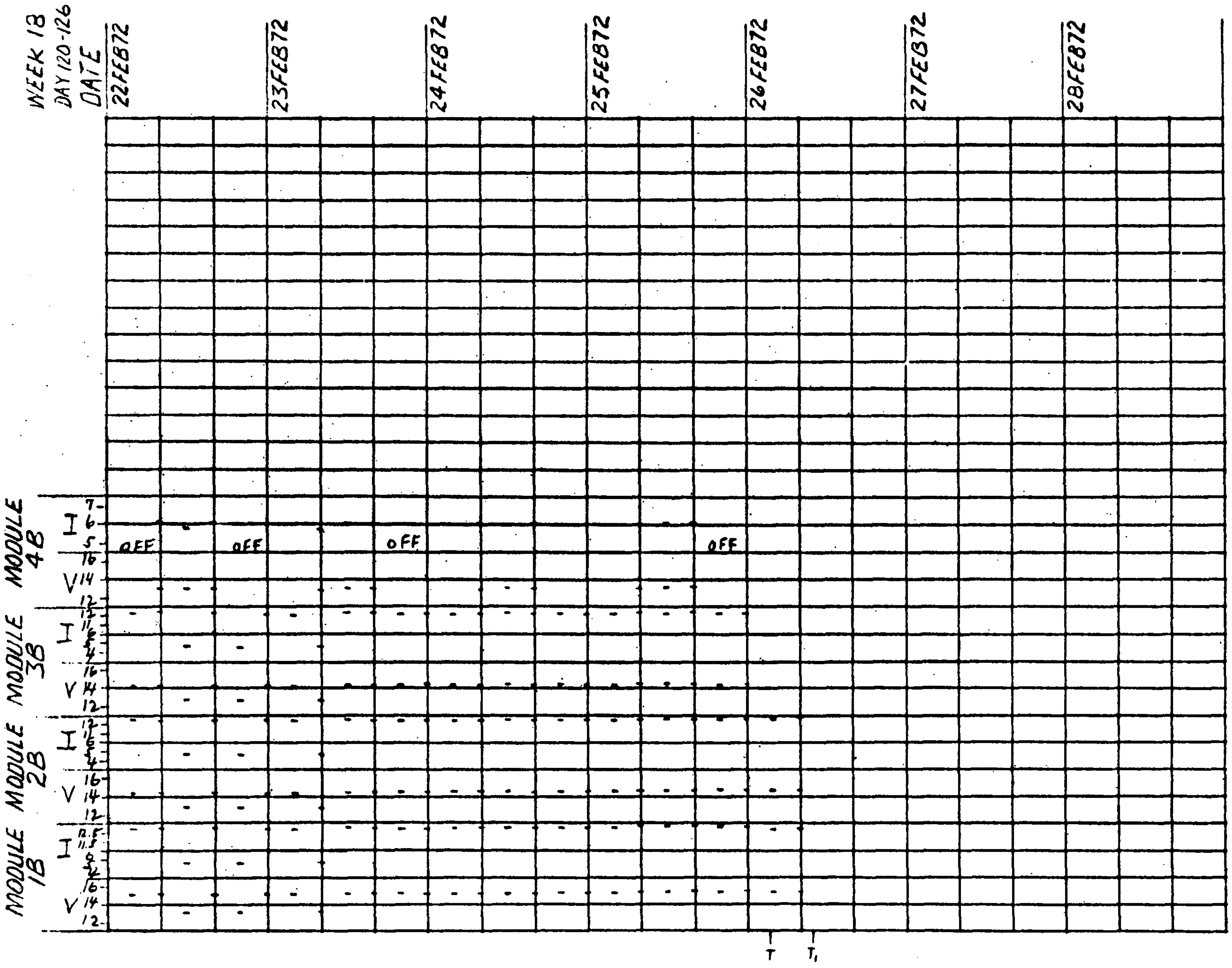

FIGURE 4-52
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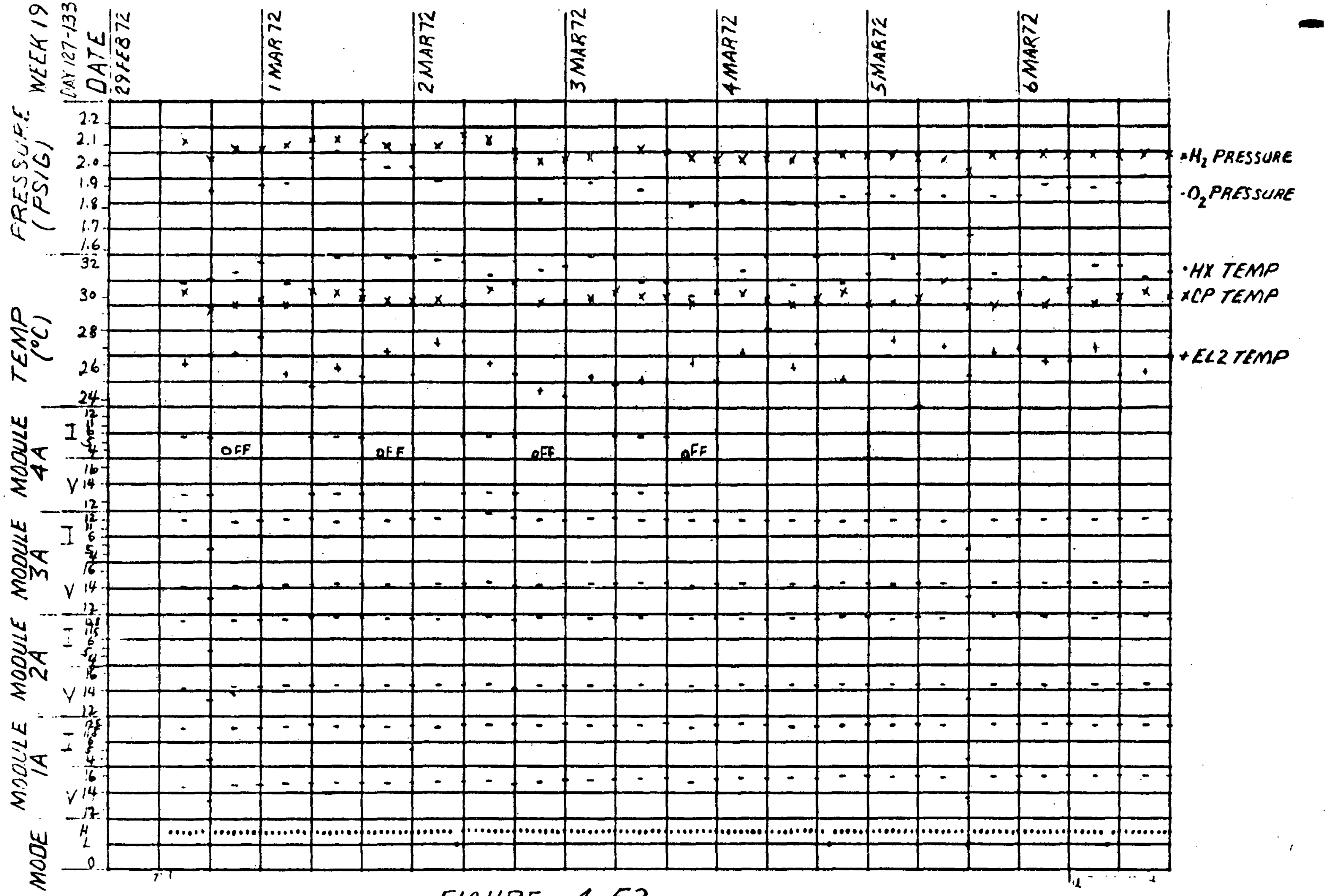

FIGURE 4-53
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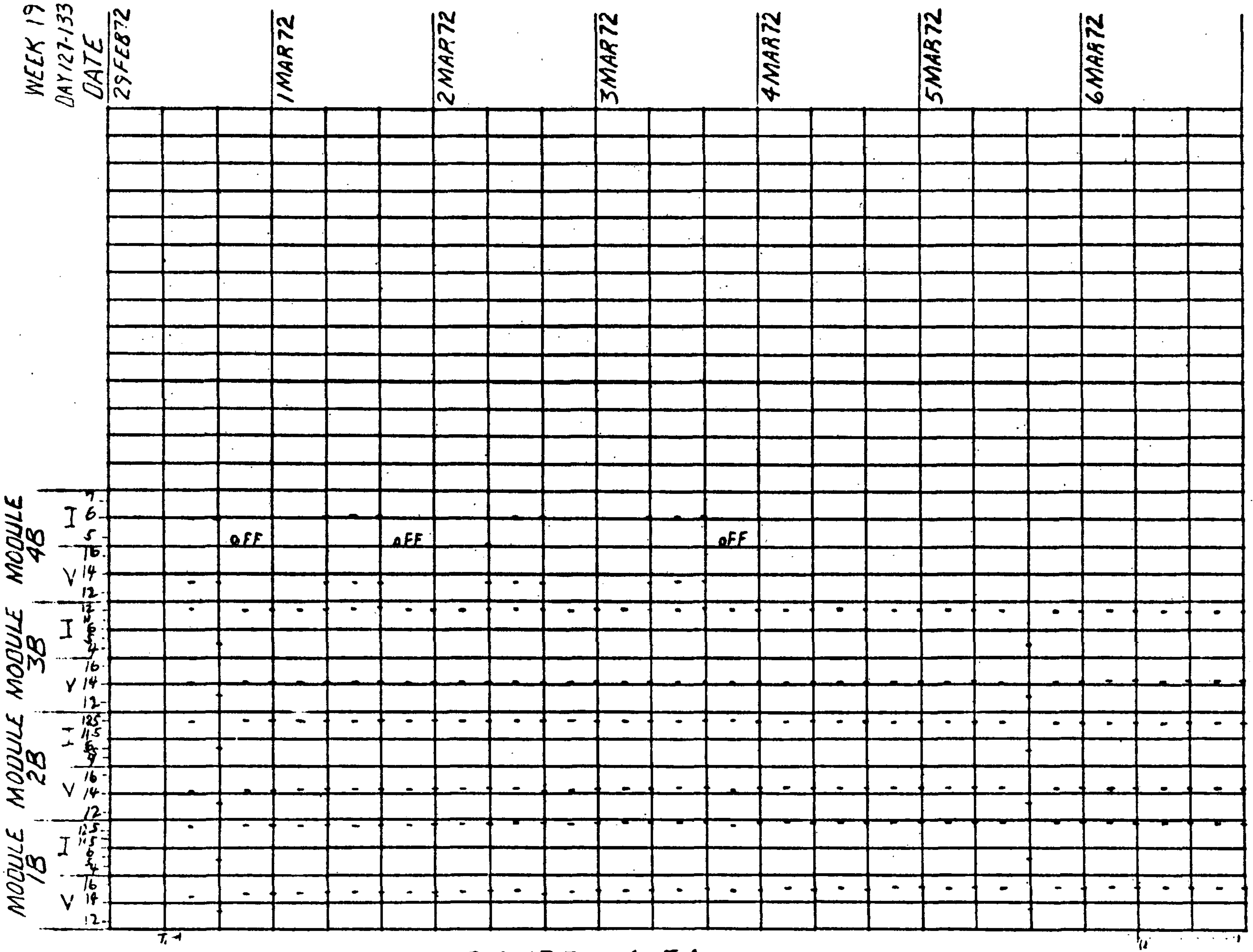

FIGURE 4-54
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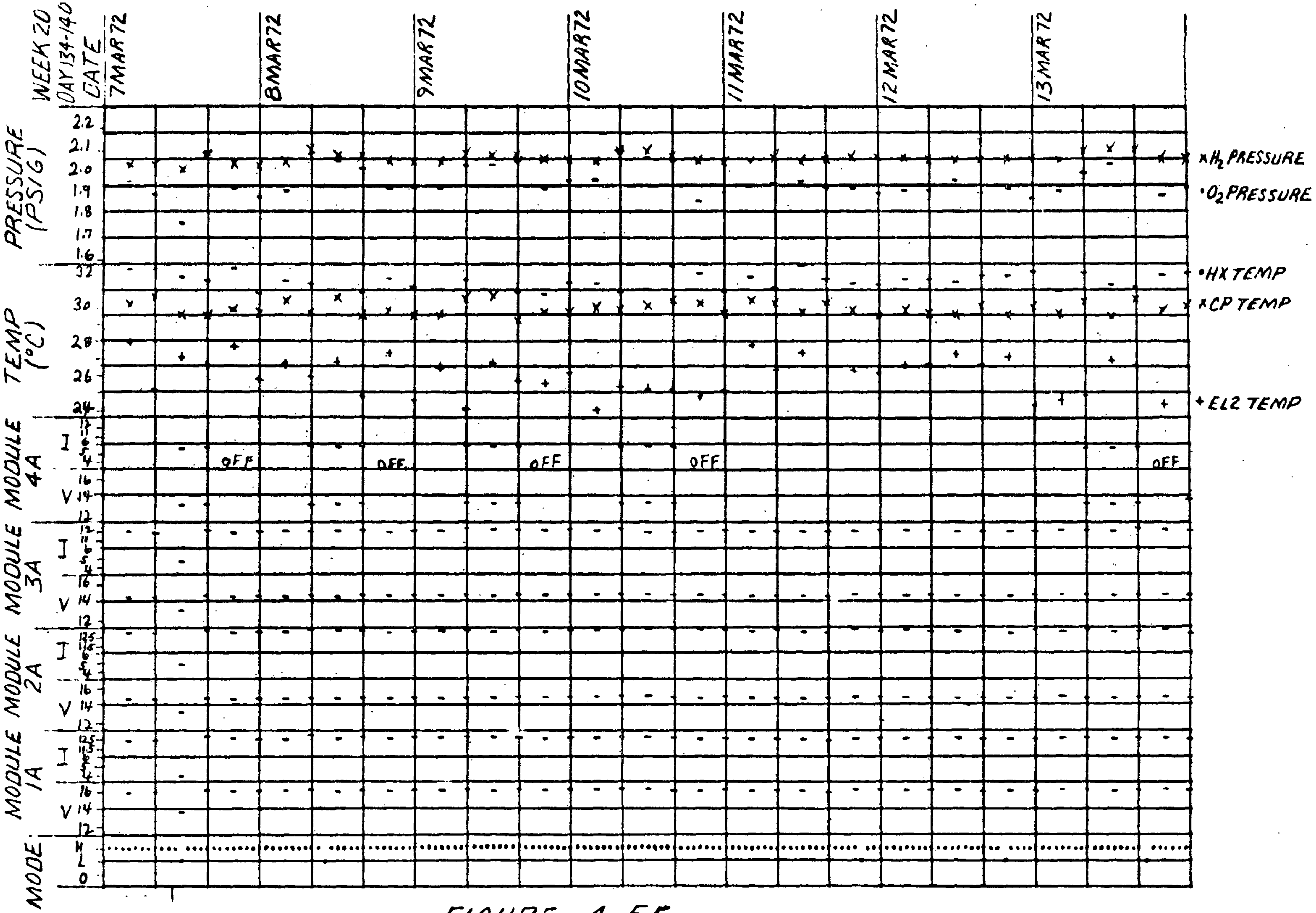

FIGURE 4-55
CELI DAILY PERFORMANCE DATA

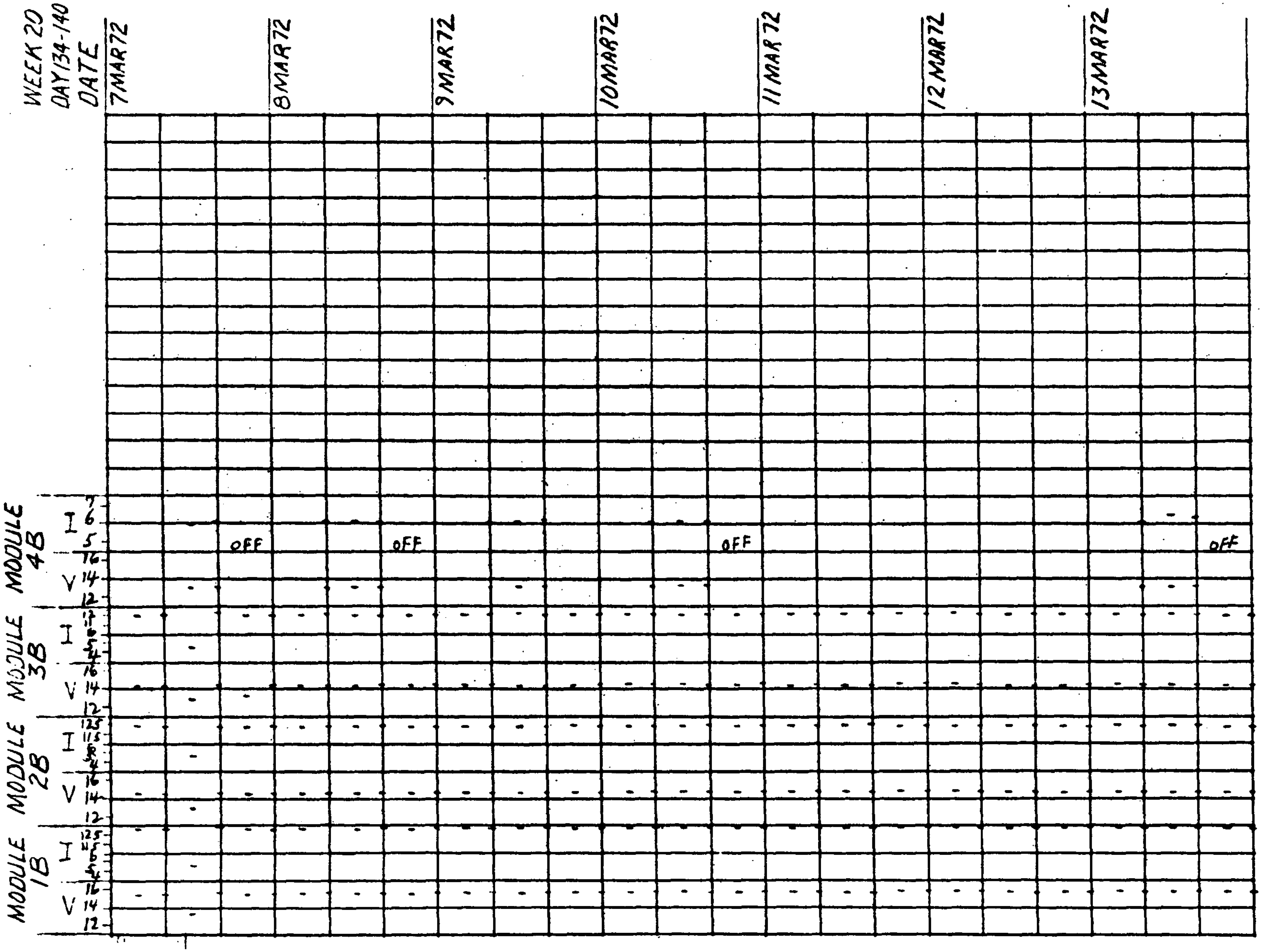

FIGURE 4-56
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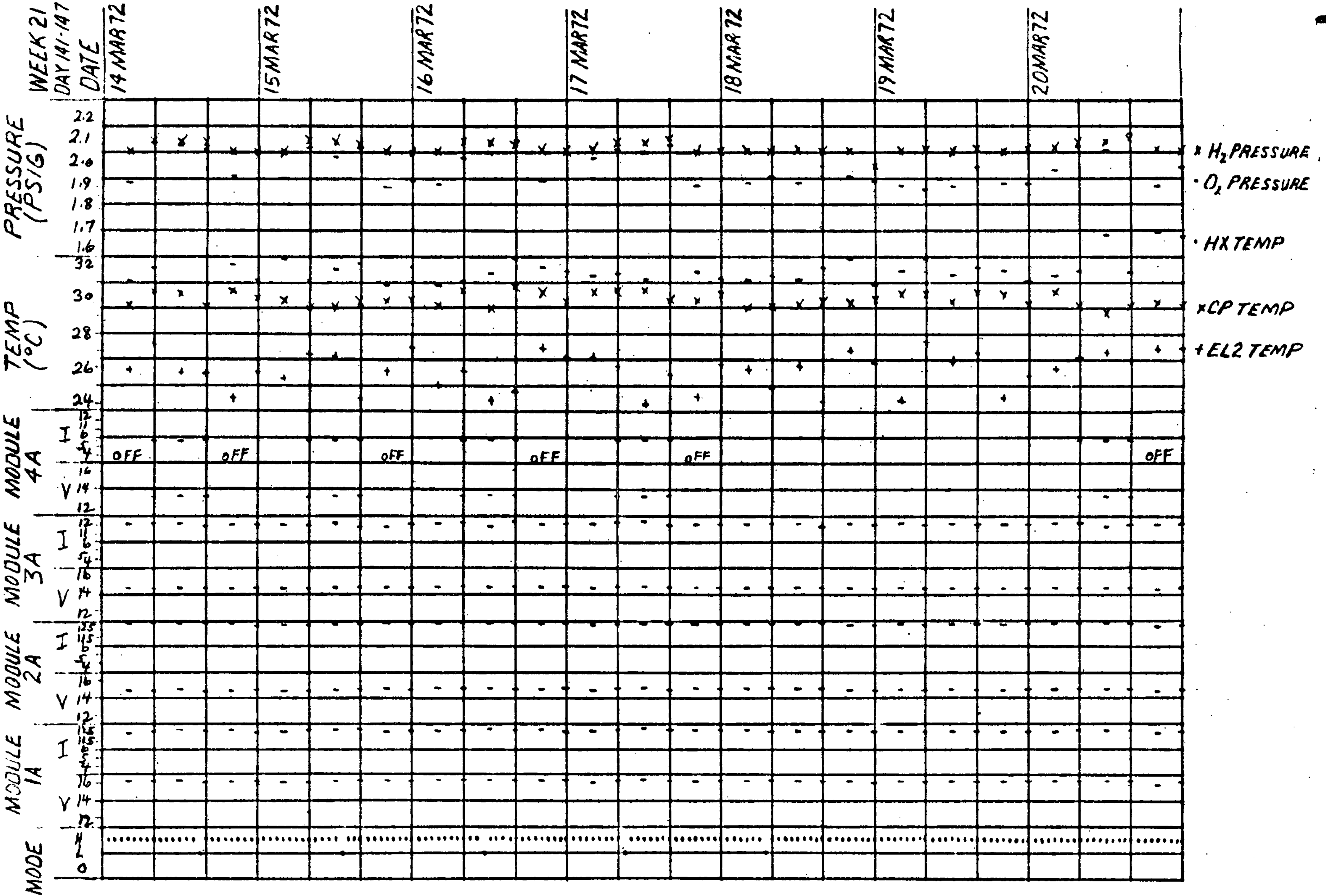

FIGURE 4-57
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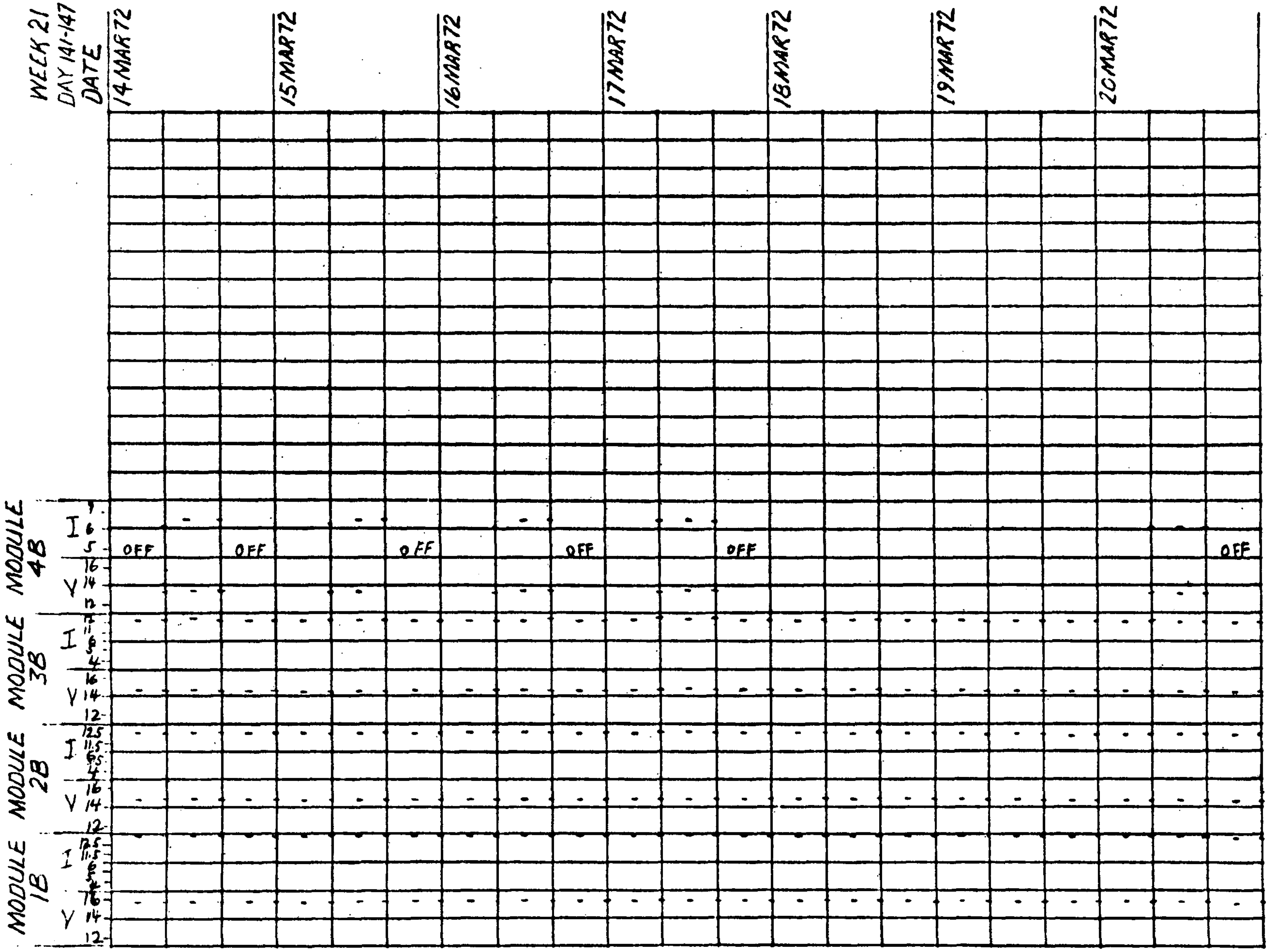

FIGURE 4-58
CEU DAILY PERFORMANCE DATA

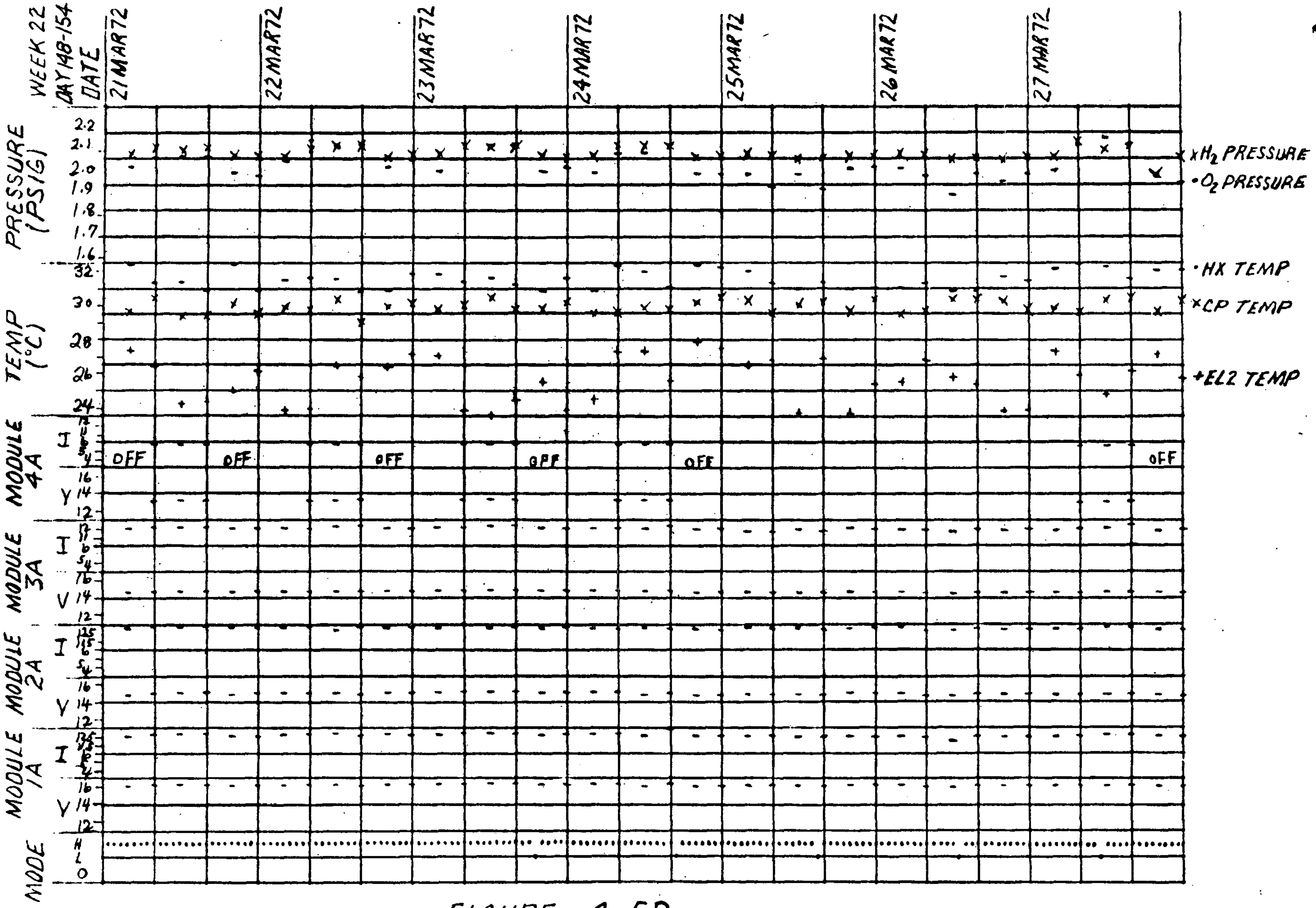

FIGURE 4-59
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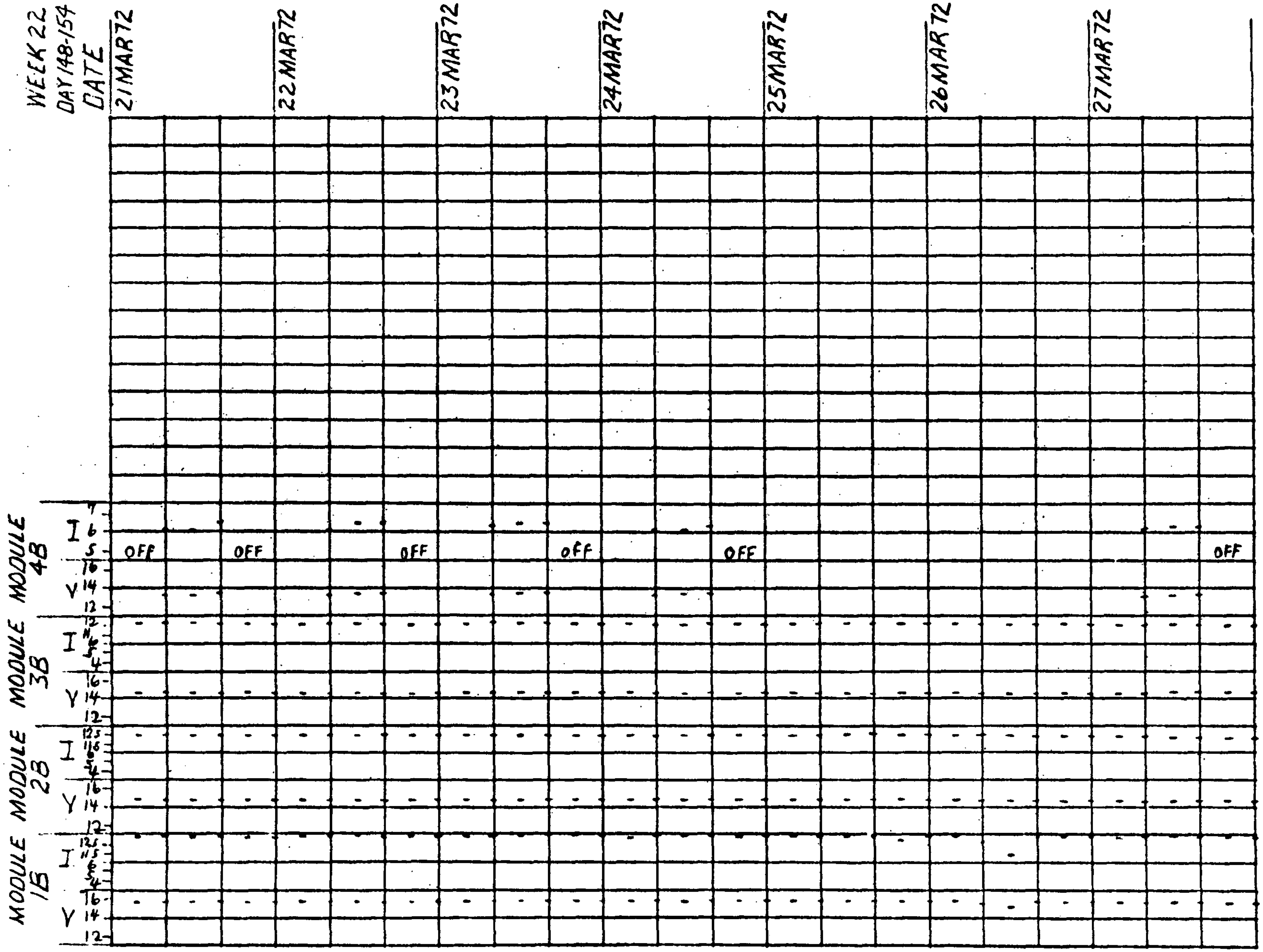

FIGURE 4-60
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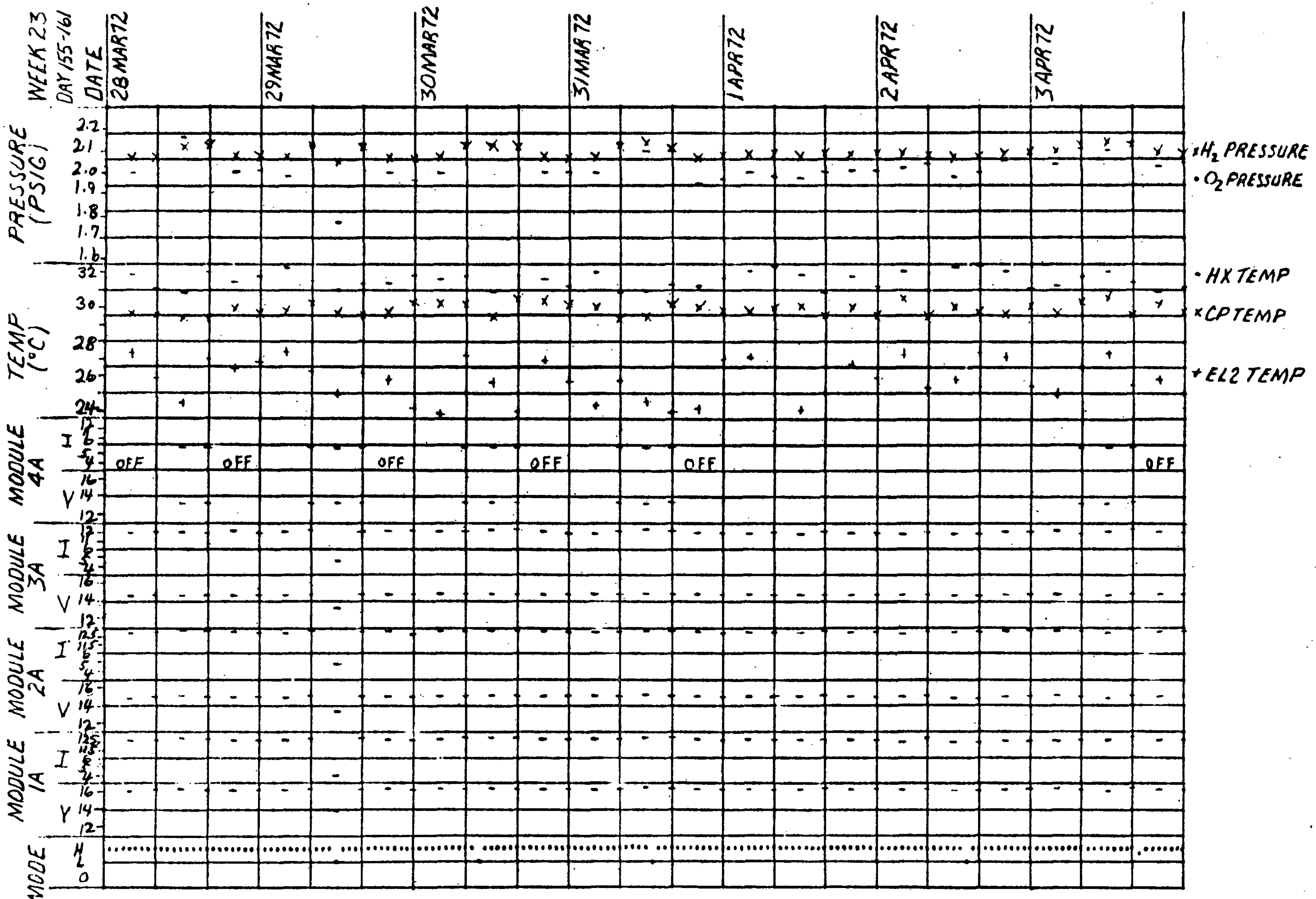


FIGURE 4-61
CEU DAILY PERFORMANCE DATA

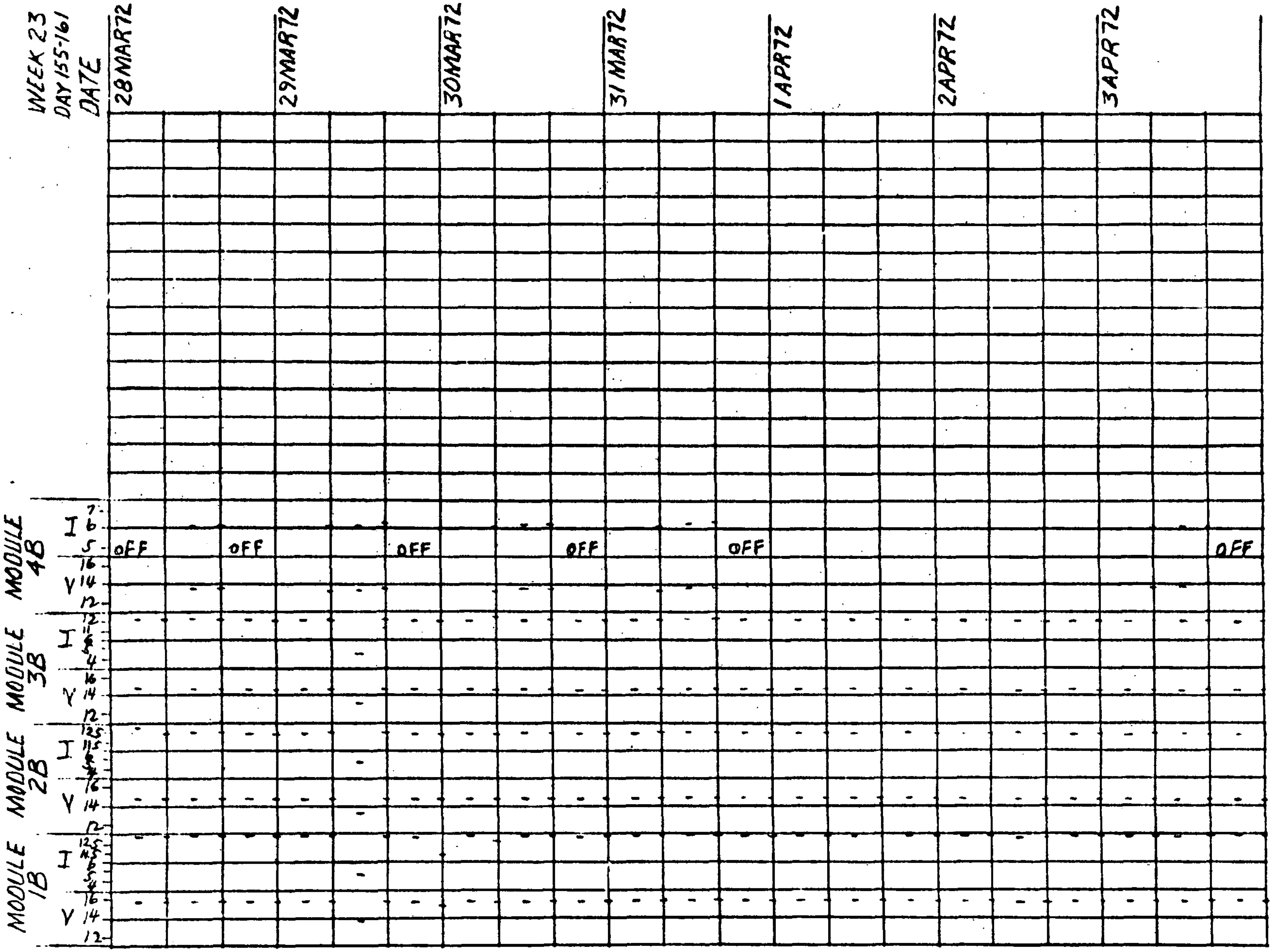


FIGURE 4-62
CEU DAILY PERFORMANCE DATA

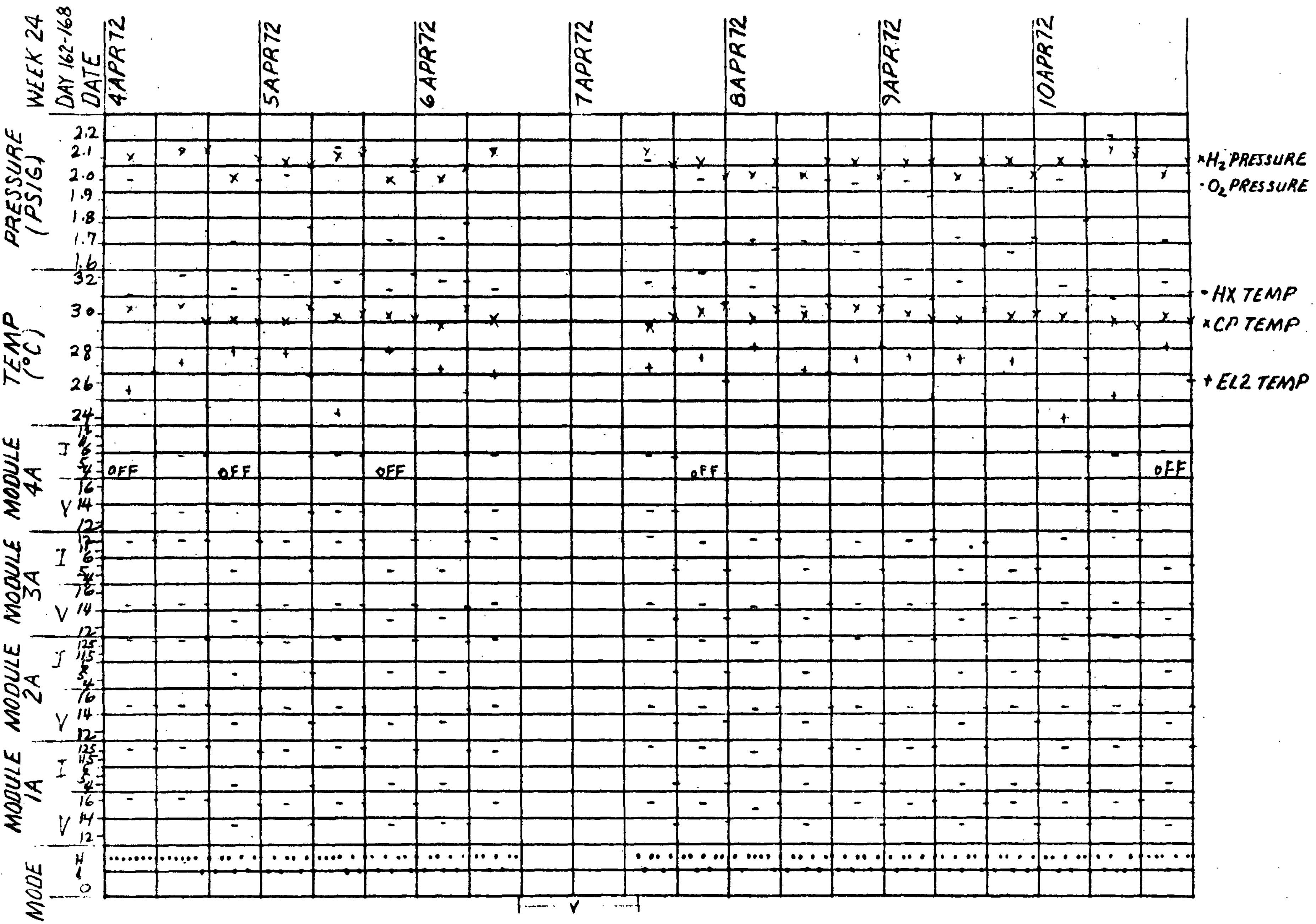


FIGURE 4-63
CEU DAILY PERFORMANCE DATA

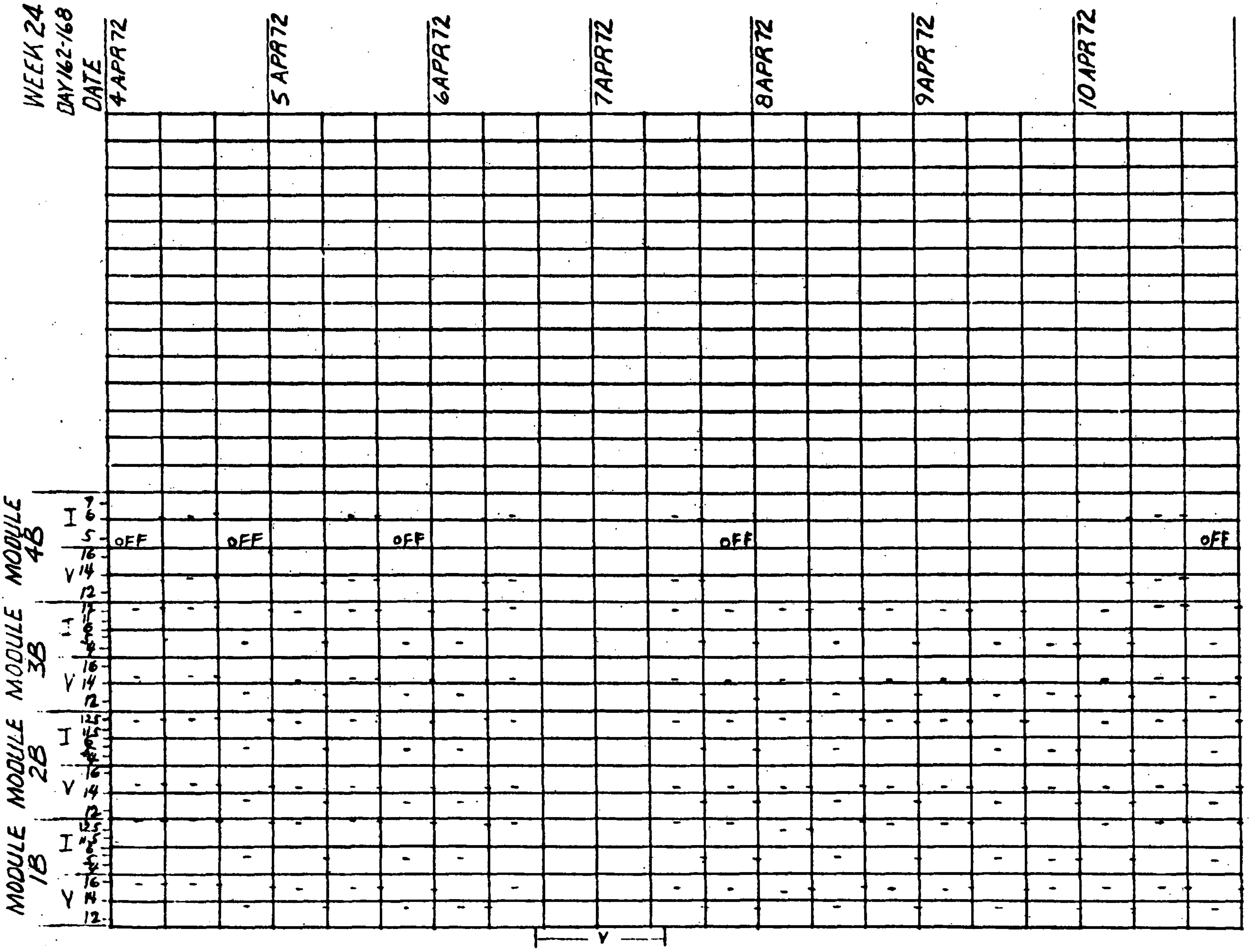


FIGURE 4-64
CEU DAILY PERFORMANCE DATA

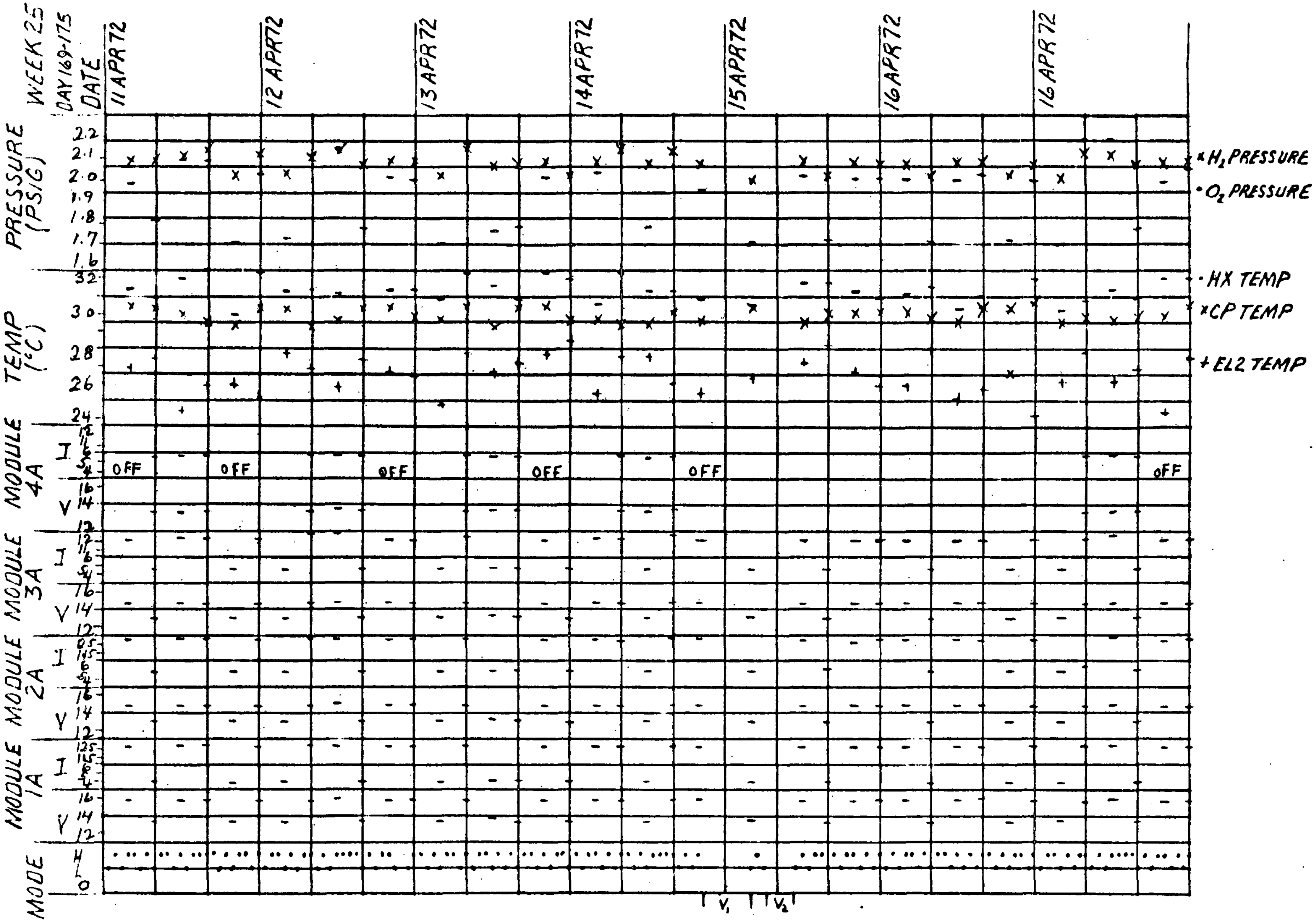


FIGURE 4-65
CEU DAILY PERFORMANCE DATA

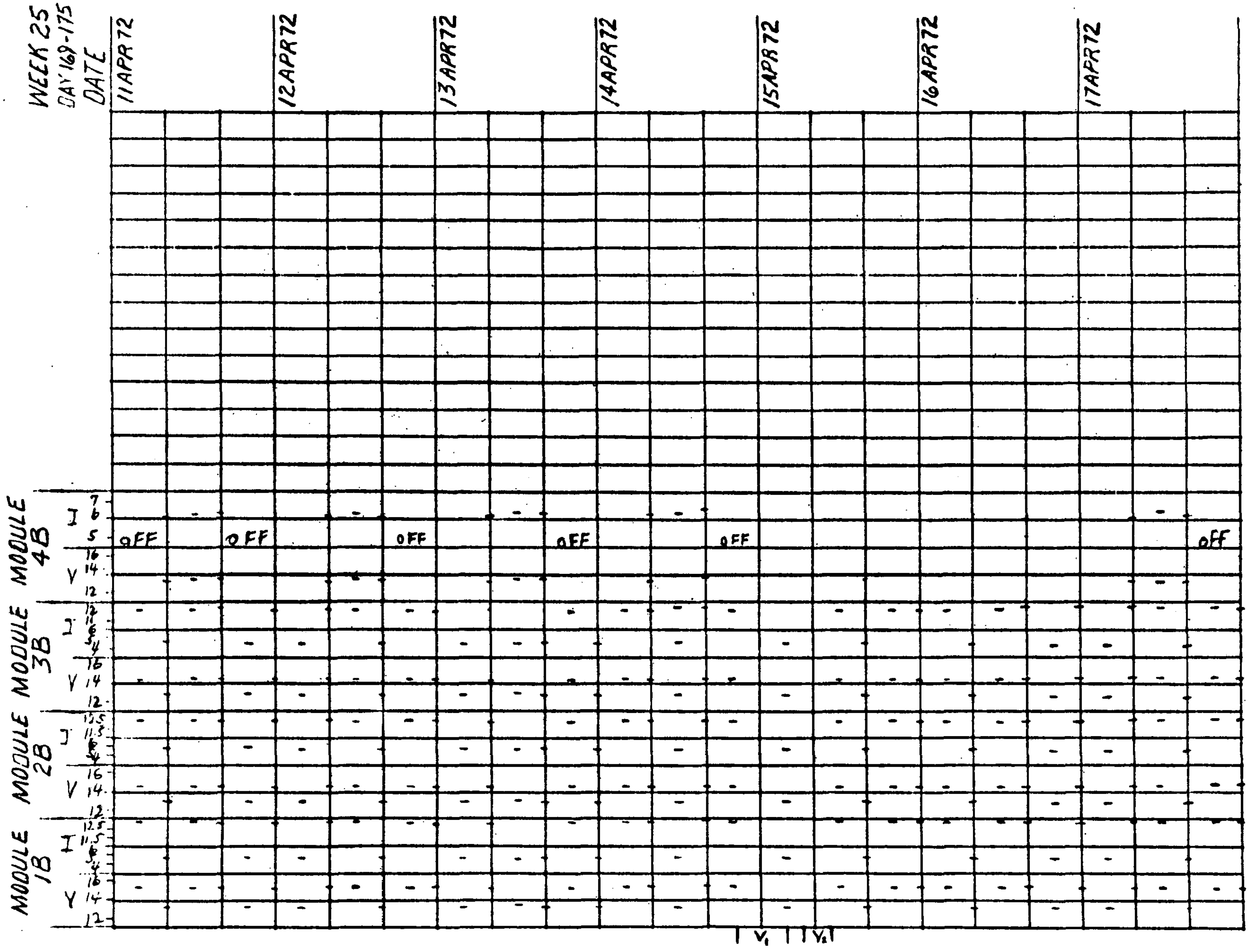


FIGURE 4-66
CEU DAILY PERFORMANCE DATA

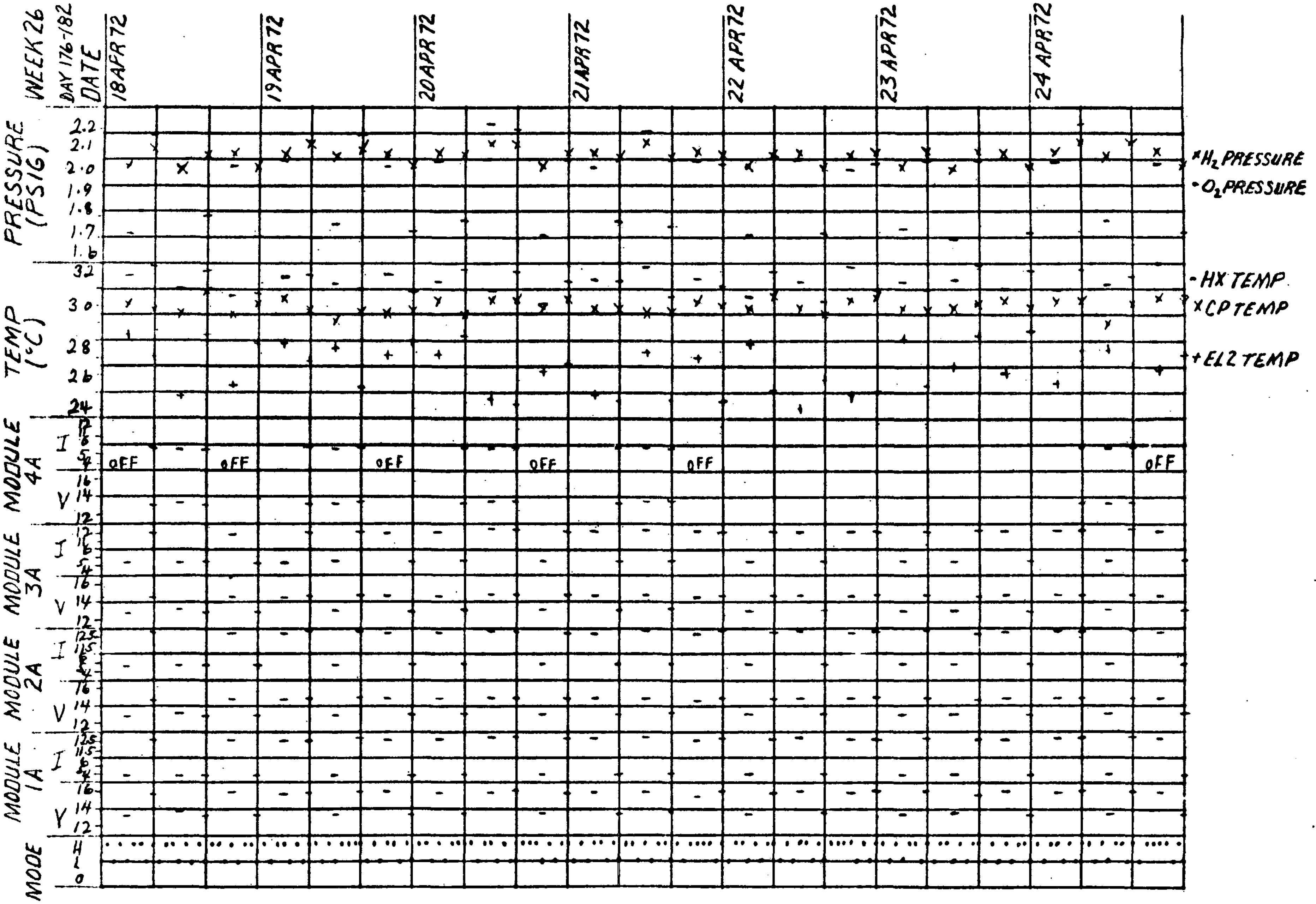


FIGURE 4-67
CEU DAILY PERFORMANCE DATA

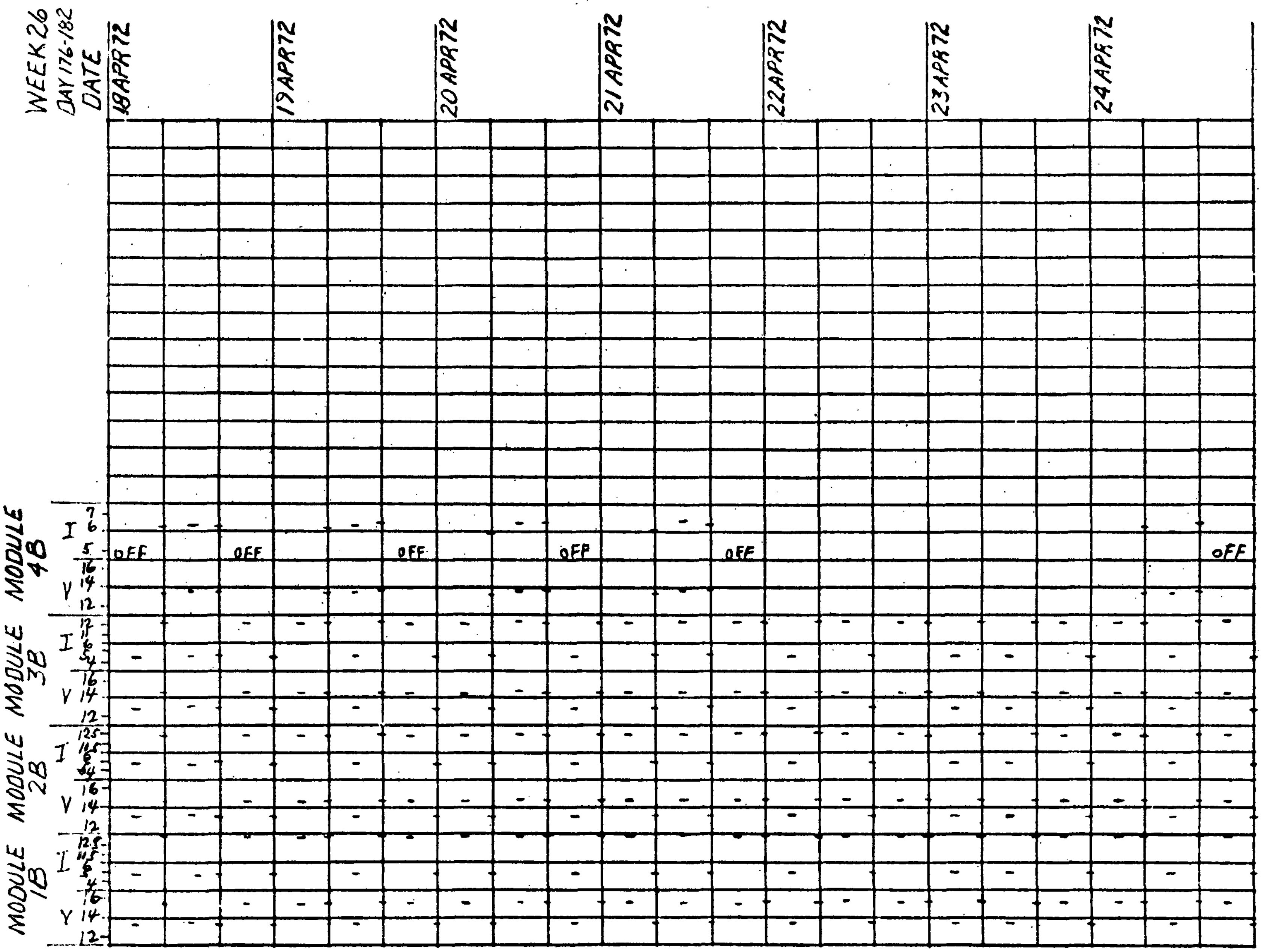


FIGURE 4-68
CEU DAILY PERFORMANCE DATA

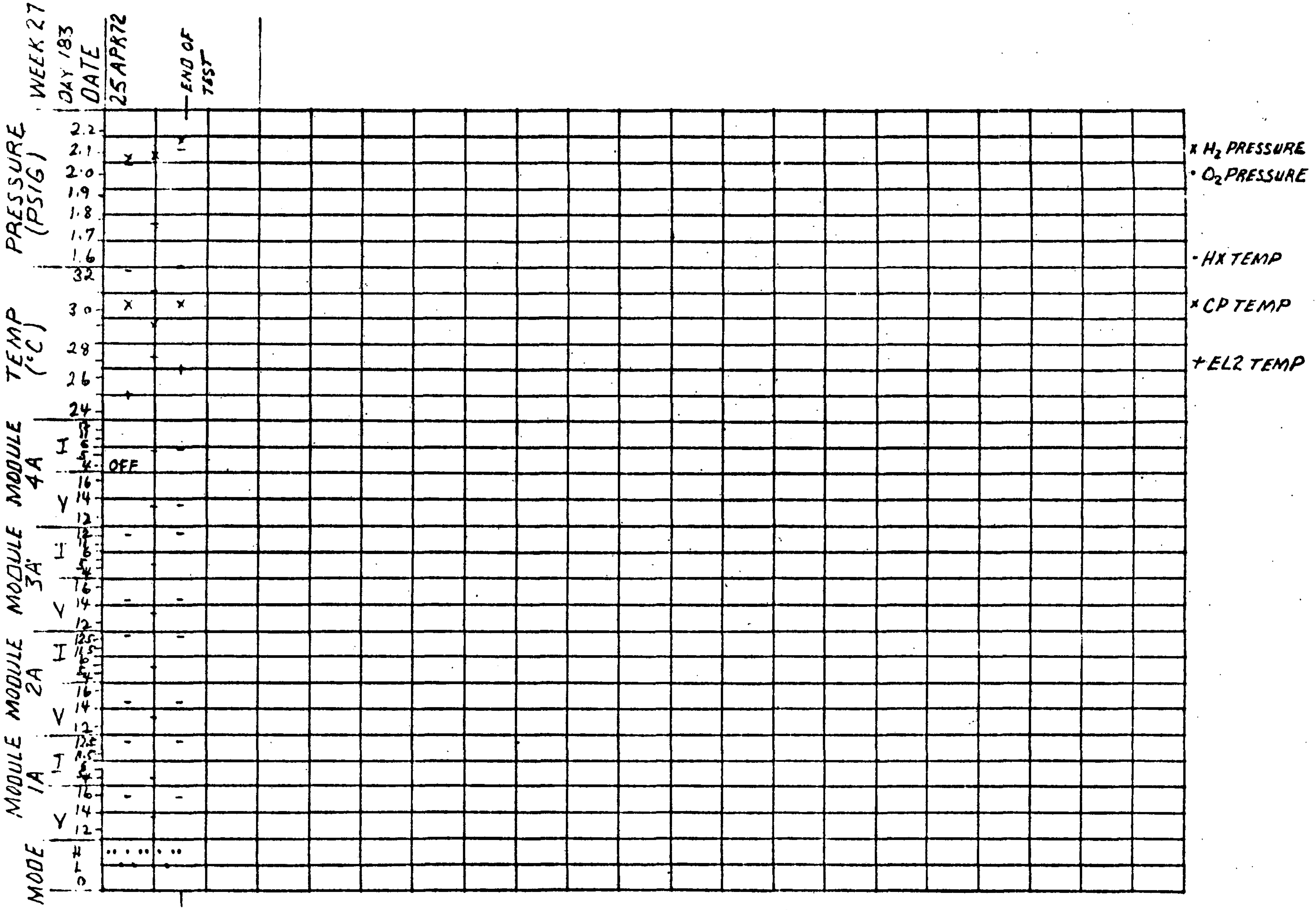


FIGURE 4-69
CEU DAILY PERFORMANCE DATA

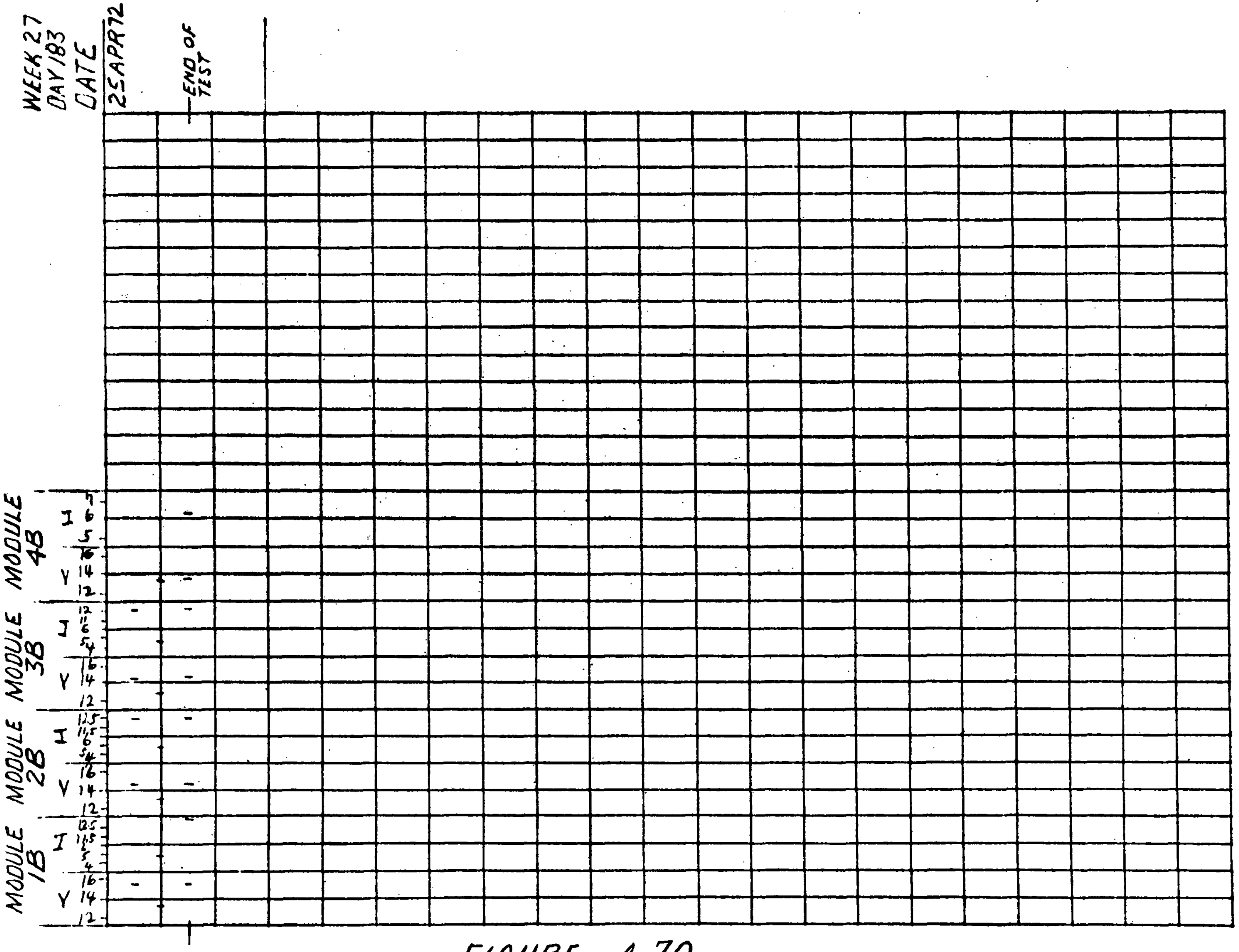


FIGURE 4-70
CEU DAILY PERFORMANCE DATA

TABLE 4-1

GRAPH NOTATIONS

A	Printer malfunction. No data printout.
B	Unit shutdown for 4 hours 35 minutes. Low system pressure. Obtained high and low for period of operation and plotted.
B1	Unit shutdown due to a high PO_2. Unit down from day 14 to day 17 at 1107. During time down tried to find out why high PO_2 shutdown. Unit operated from day 17, 1107 to 1645. Had to shutdown because of a fitting breaking at flowmeter. Data plotted for period of operation.
B2	Unit down from Day 17, 1645 to day 18, 1540. While down, replaced fitting and O_2 and H_2 solenoid valves. Unit operated from 1540 to 2153 on day 18. Shutdown due to low system pressure. At 2000 hours data showed module 4 operated at high mode. Data plotted for period of operation.
B3	Unit shutdown on day 18, 2153 On day 19, put unit in manual mode purge on, pump on and water feed auto. Unit down until day 21, 1002. Unit on line day 21 at 1002 to day 21, 1730. Data plotted for period of operation.
B4	Unit shutdown day 21, 1730 per NASA instruction. Data showed unit had tried to startup when unit was in shutdown mode. Unit on line at 0802 to 1030. During period while operating, module 4A and B had high readings on current and voltage. During shutdown, changed integrated circuits on cards W2 and W3. These chips work with module 4. At 1053 restarted system. Data plotted, showing where current and voltage were high.
C	From day 16, module 4 turned off at night and on weekends. Data will be plotted during operating hours.
D	System shutdown 0206 day 37 - low system pressure. Restarted 1630 day 38.

TABLE 4-1 (Continued)

E	System shutdown 0752 day 39 - low system pressure. Restarted 1620 day 39.
F	System shutdown 0852 day 47 - high oxygen partial pressure. Restarted 1521 day 49.
F_1	System shutdown 0755 day 50 - Manual shutdown, no product gas flow through bubblers. Restarted 0800 day 51.
G	Module 4 shutoff for Christmas holiday.
G_1	Data acquisition printer malfunction. Reloaded computer. Data plotted for remaining period.
H	Printer malfunction, insufficient data available for plotting.
H_1	Computer and printer problems, malfunctions repaired, available data plotted.
H_2	No data available for module 4, available data on modules 1, 2 and 3 plotted.
I	System shutdown, fitting on module 4 broke.
J	Start of cyclic mode.
J_1	Due to cyclic mode of operation, data is plotted for high mode only, no low mode data available.
K	System shutdown due to low system pressure.
L	System on line.
L_1	System put in cyclic mode.
L_2	System shifted from cyclic mode to continuous mode.
L_3	System put in cyclic mode.
L_4	System shifted from cyclic mode to continuous mode.

NOTE: 1. On days 51 and 52, module 1A had low and erratic current and voltage. On days 55 and 56, Module 3B experienced the same phenomena. Since then, the voltages and currents remedied themselves except for an occasional low reading. The problem seemed to be in the current regulator cards.

TABLE 4-1 (Continued)

M	System shutdown 1811 on 2 February (test day 100) due to malfunctioning integrated circuit. System restarted at 0941 on 4 February (test day 102). Replaced chip on card W2.
M_1	Initiated continuous mode of operation.
N	System shutdown to make modifications to card SC6. Unit was down for 2 hours.
N_1	System back in cyclic mode at 1753.
P	System shutdown due to low system pressure. Wiring error found on modification to card SC6.
P_1	Unit back in continuous mode of operation within 2 hours.
Q	System shutdown by resident engineer to troubleshoot problem in circuit on card SC6.
Q_1	System on and operating in cyclic mode within 6 hours.
Q_2	System shifted from cyclic mode to continuous mode of operation.
R	System shutdown manually to install new stainless steel Teflon-coated fittings.
S	Initiated increase in module current to maximum output of 4.54 kg/day (10.0 pounds/day) of oxygen. Rate of increase to be 0.23 kg/day (0.5 pound/day) of oxygen.
T	Module 3 shutdown by circuit breaker. Data printout indicated excess of 20 amperes. Circuit noise was the cause. Circuit card was replaced.
T_1	System shutdown. Additional filter capacitor added to card W2, chip Z1 to eliminate circuit noise.
U	Module 4 would not turn on, cause unknown. Problem disappeared the following day.
V, V_1 & V_2	At these points, there was no data available to plot, due to trouble with the Data Acquisition System.

FIGURE 4-71
MODULE 1 SUMMARY PERFORMANCE DATA

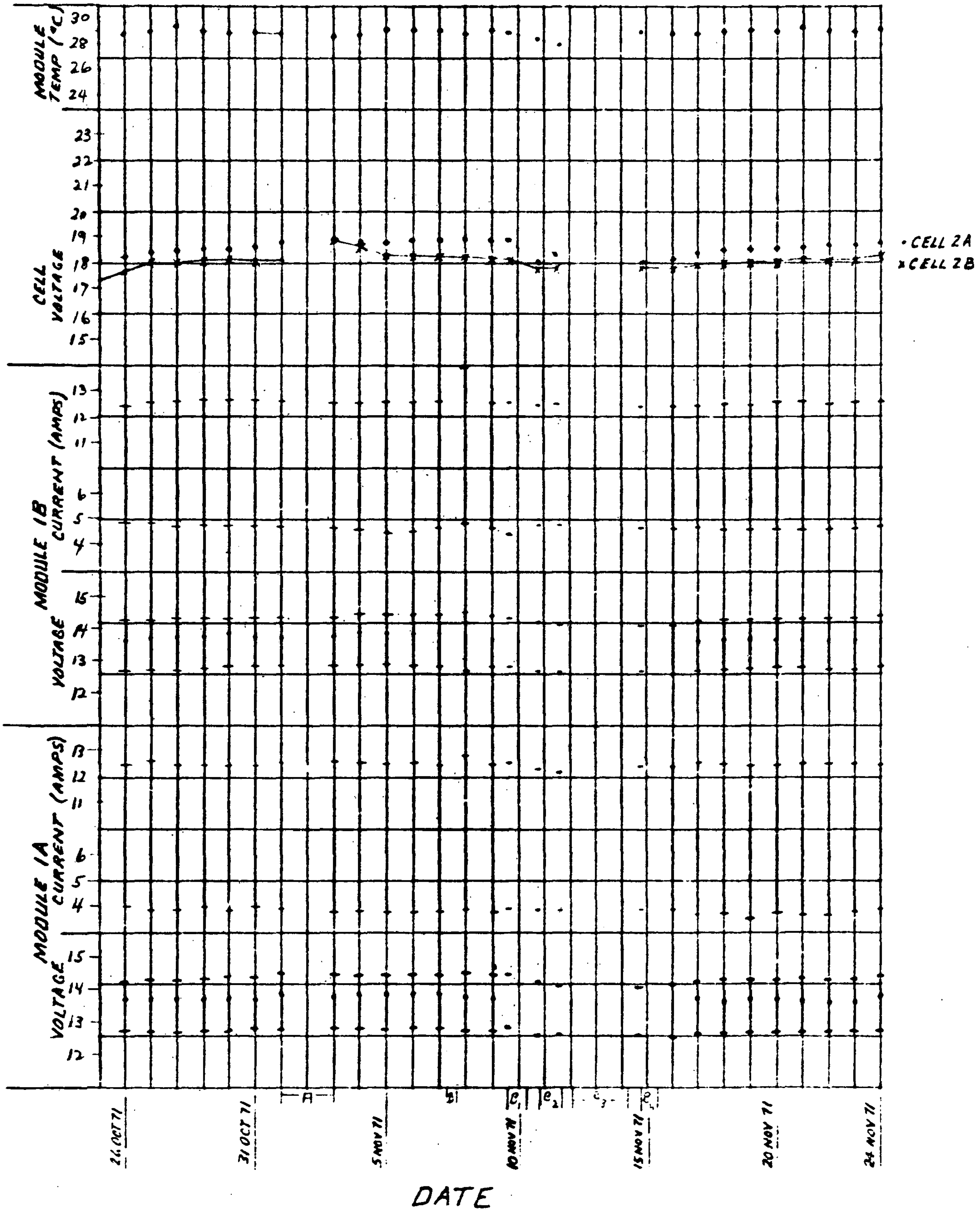


FIGURE 4-72

MODULE 2 SUMMARY PERFORMANCE DATA

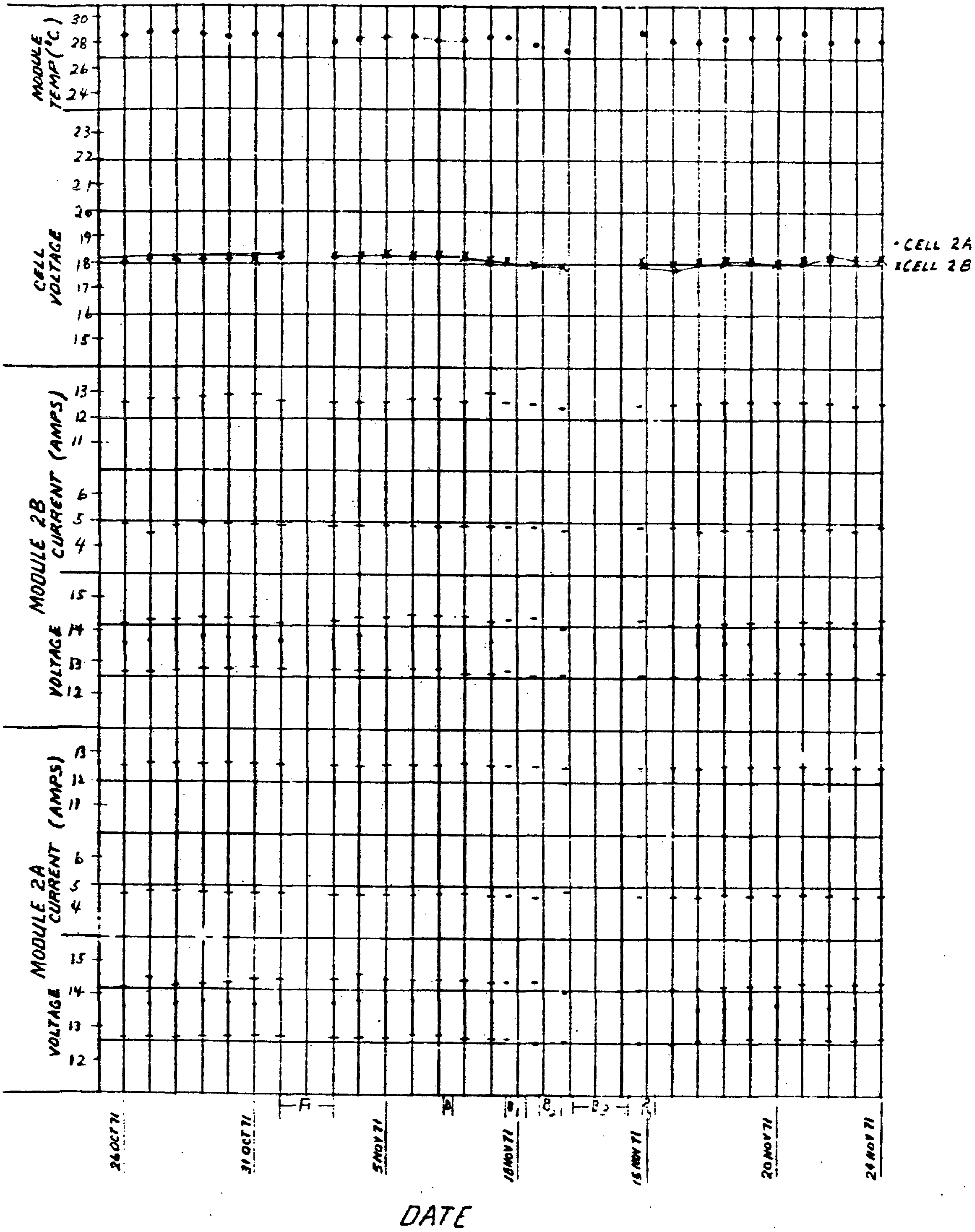
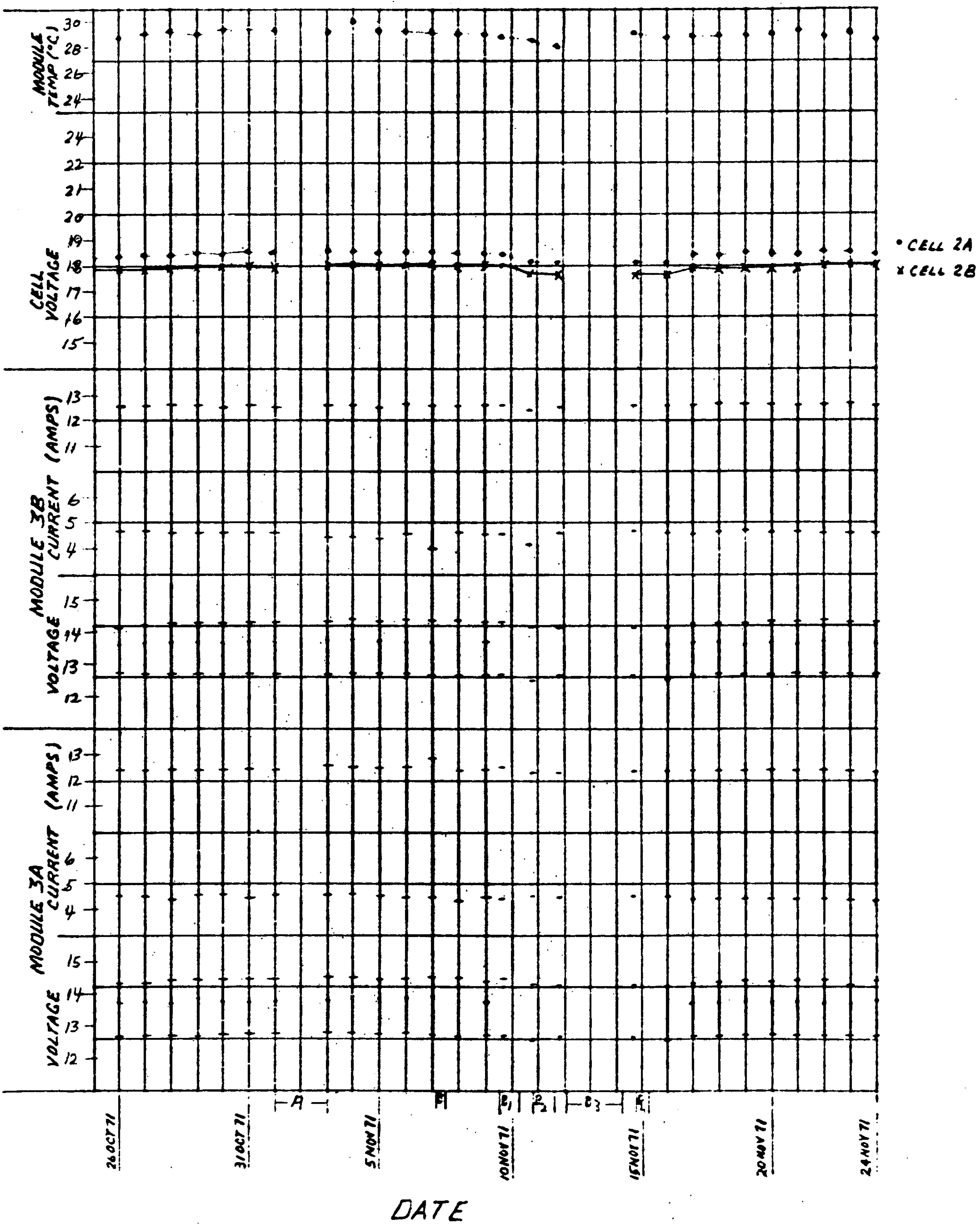


FIGURE 4-73
MODULE 3 SUMMARY PERFORMANCE DATA



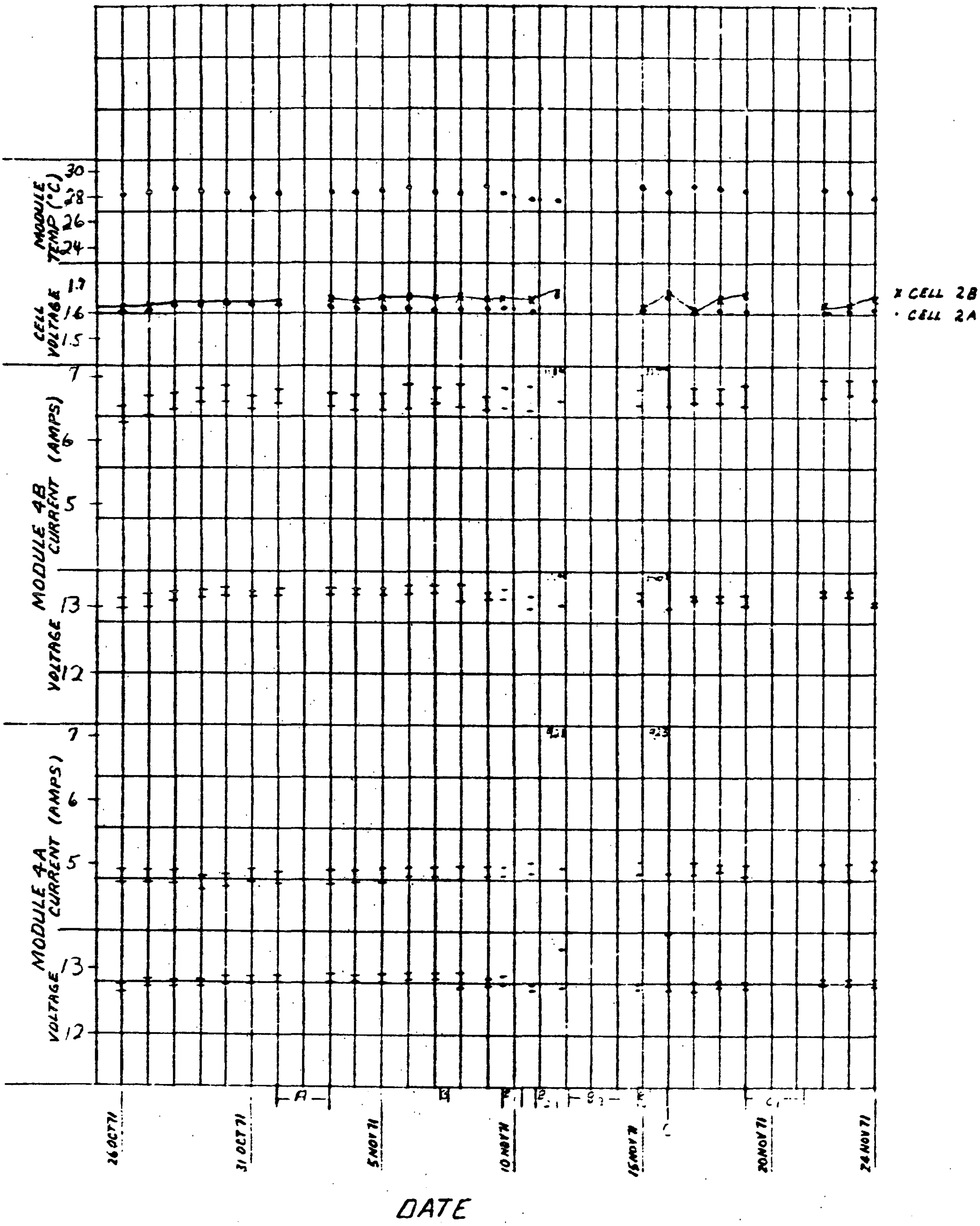


FIGURE 4-74
MODULE 4 SUMMARY PERFORMANCE DATA

FIGURE 4-75

MODULE I SUMMARY PERFORMANCE DATA

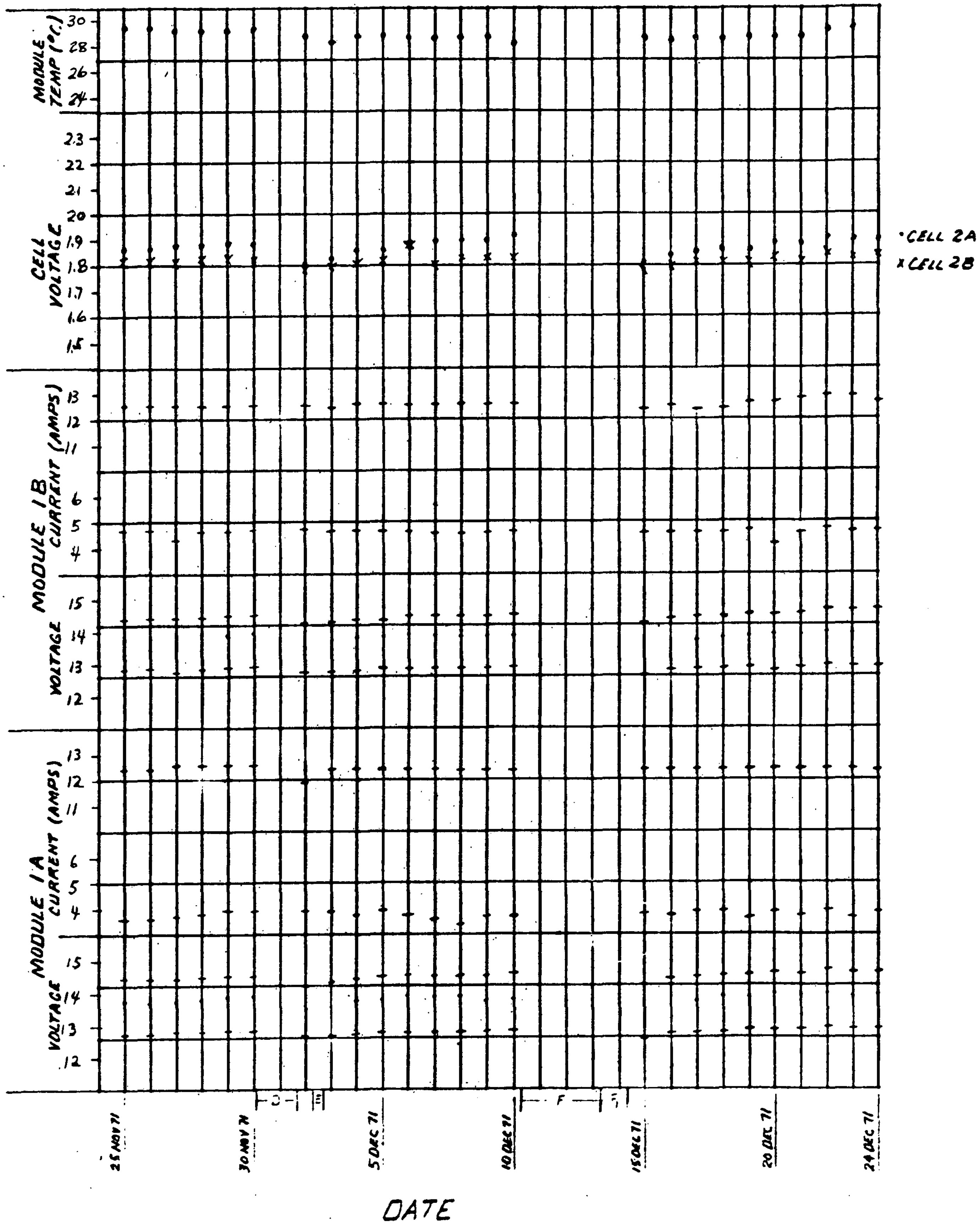


FIGURE 4-76
MODULE 2 SUMMARY PERFORMANCE DATA

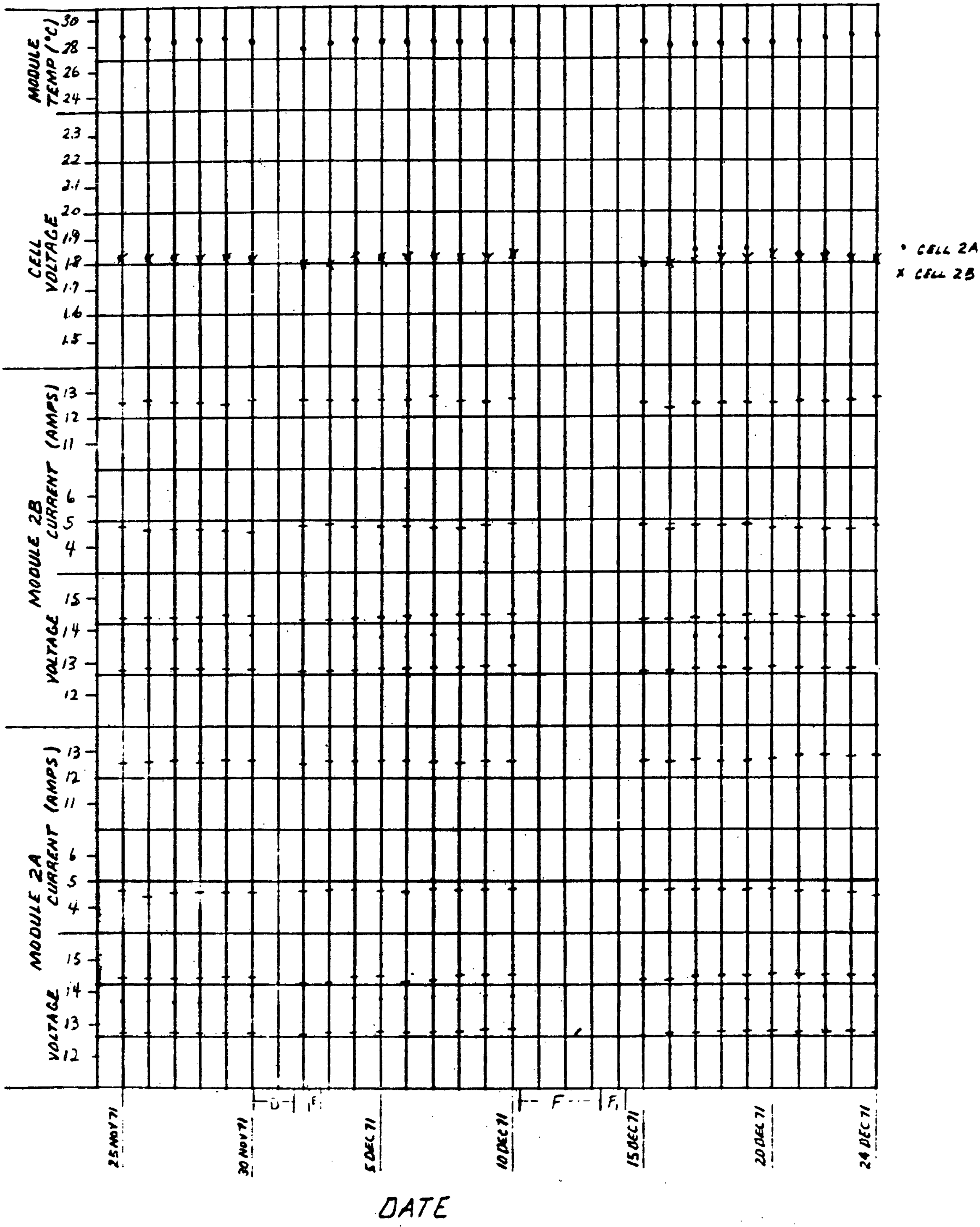


FIGURE 4-77

MODULE 3 SUMMARY PERFORMANCE DATA

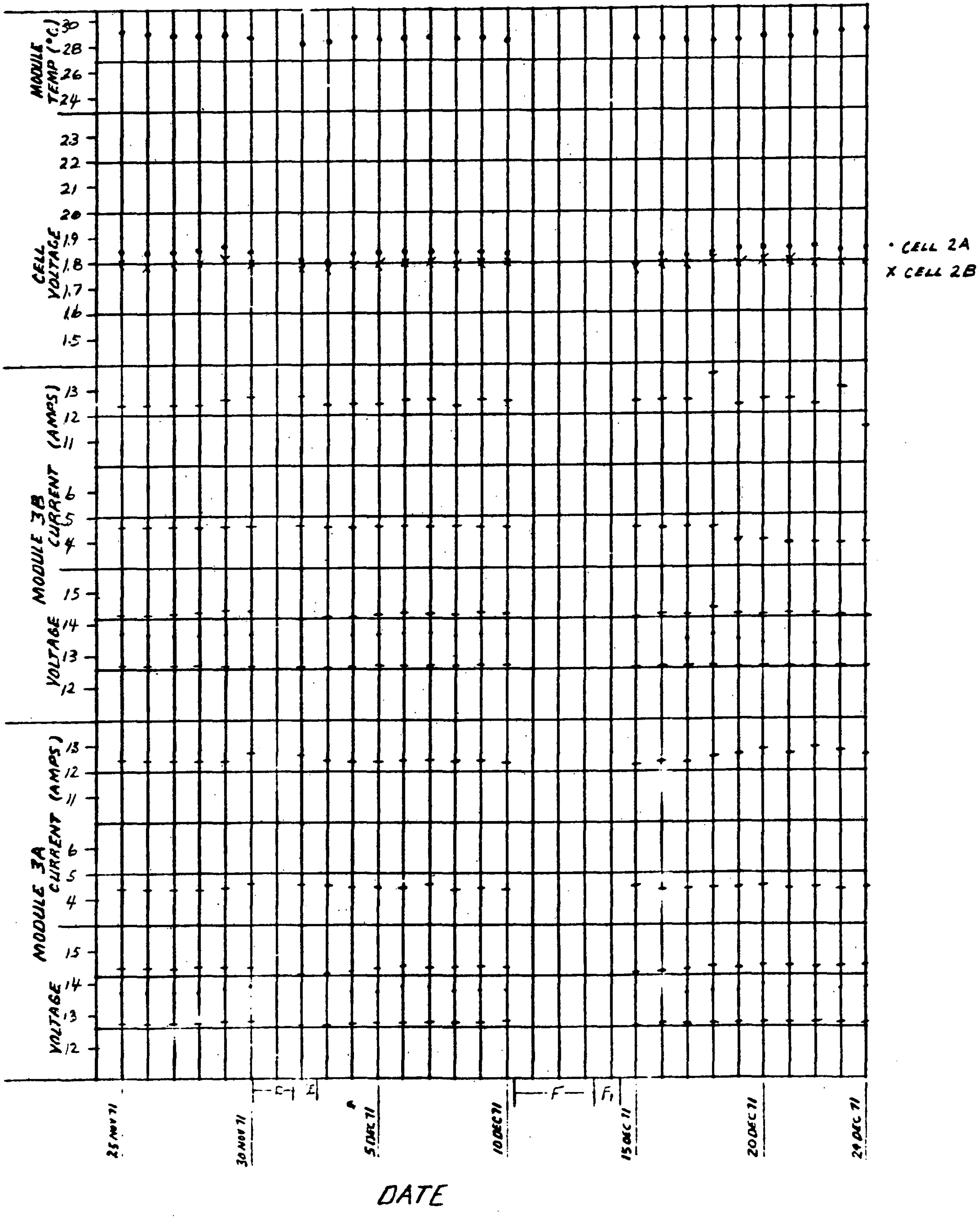


FIGURE 4-78

MODULE 4 SUMMARY PERFORMANCE DATA

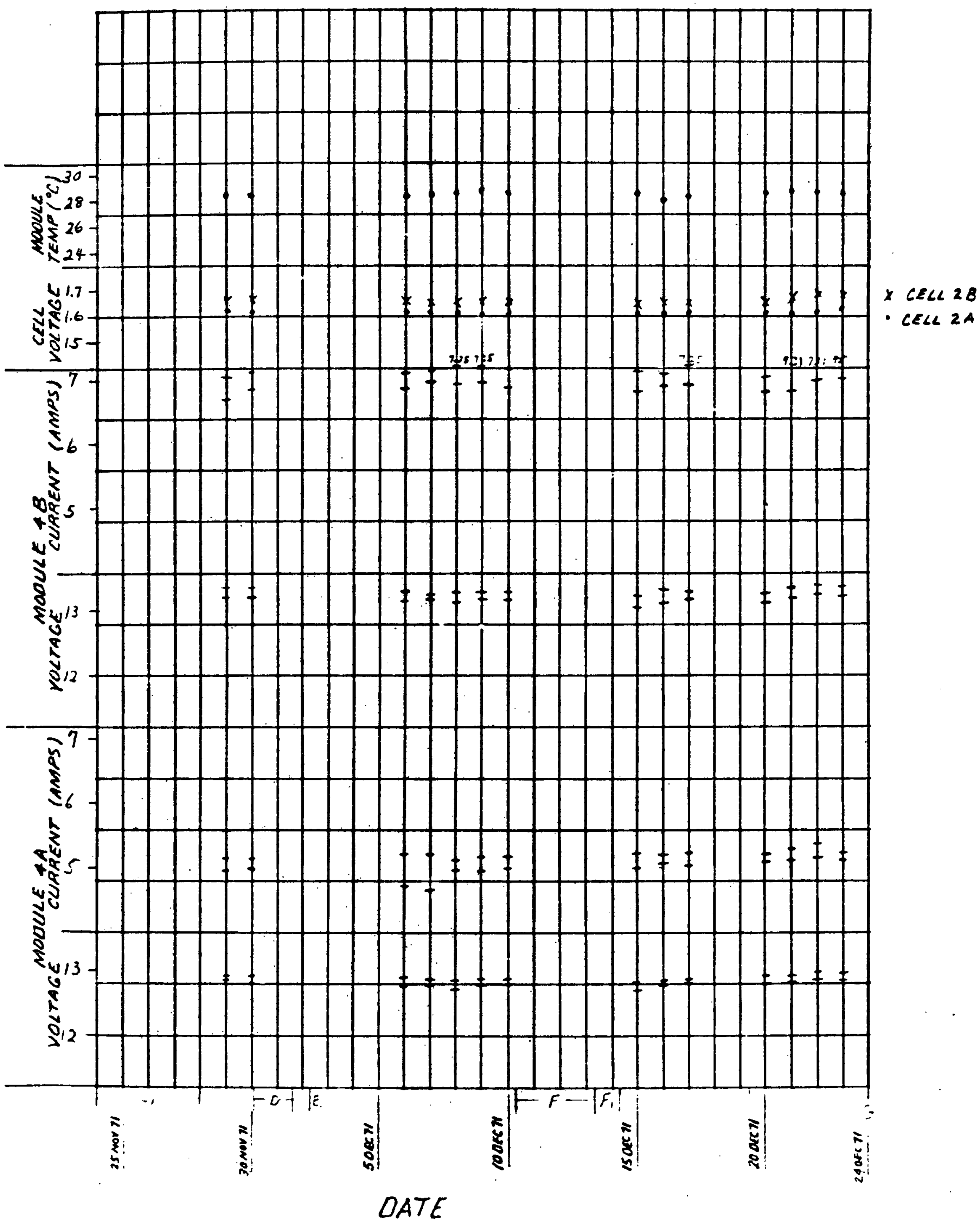


FIGURE 4-79

MODULE I SUMMARY PERFORMANCE DATA

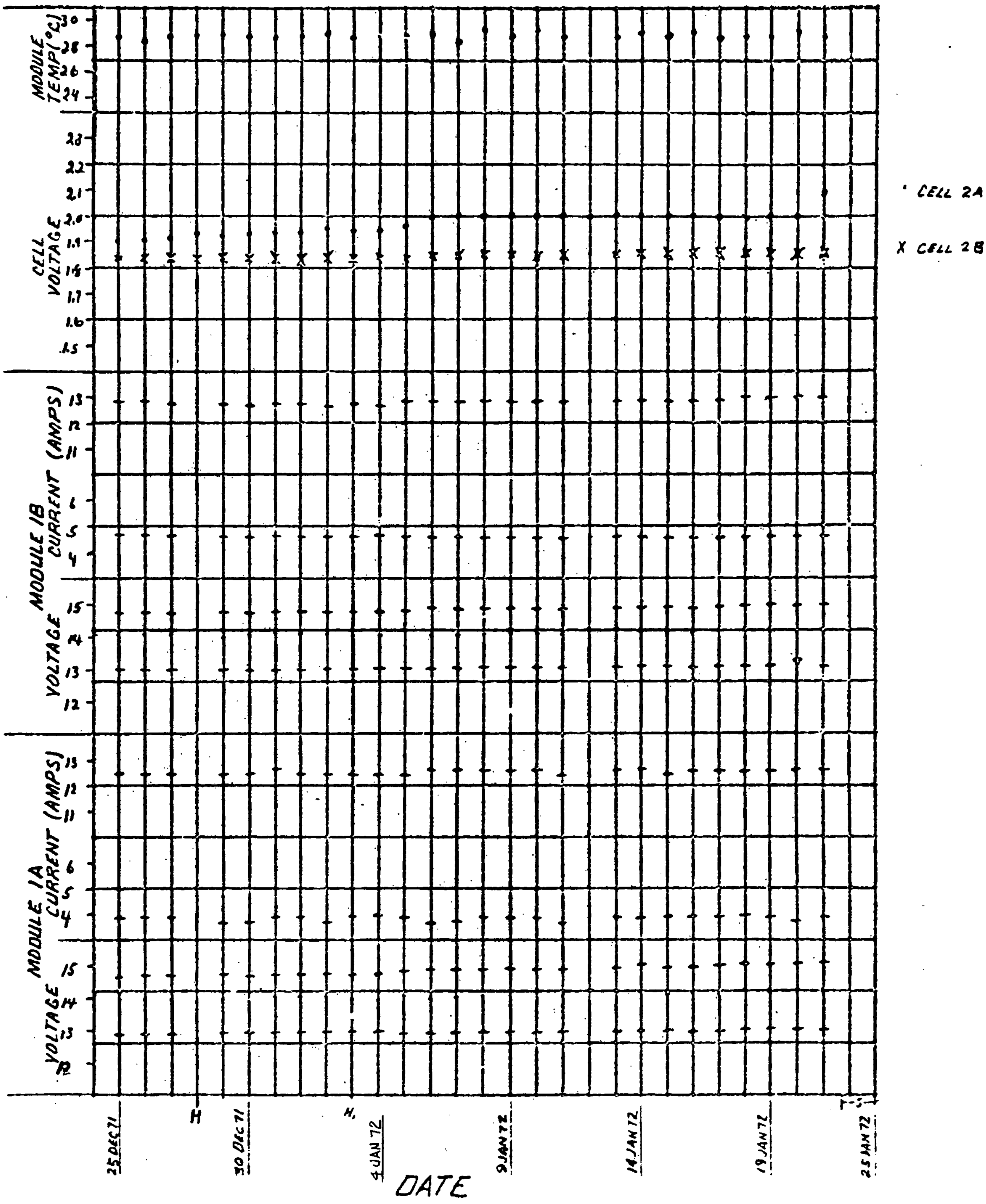


FIGURE 4-80

MODULE 2 SUMMARY PERFORMANCE DATA

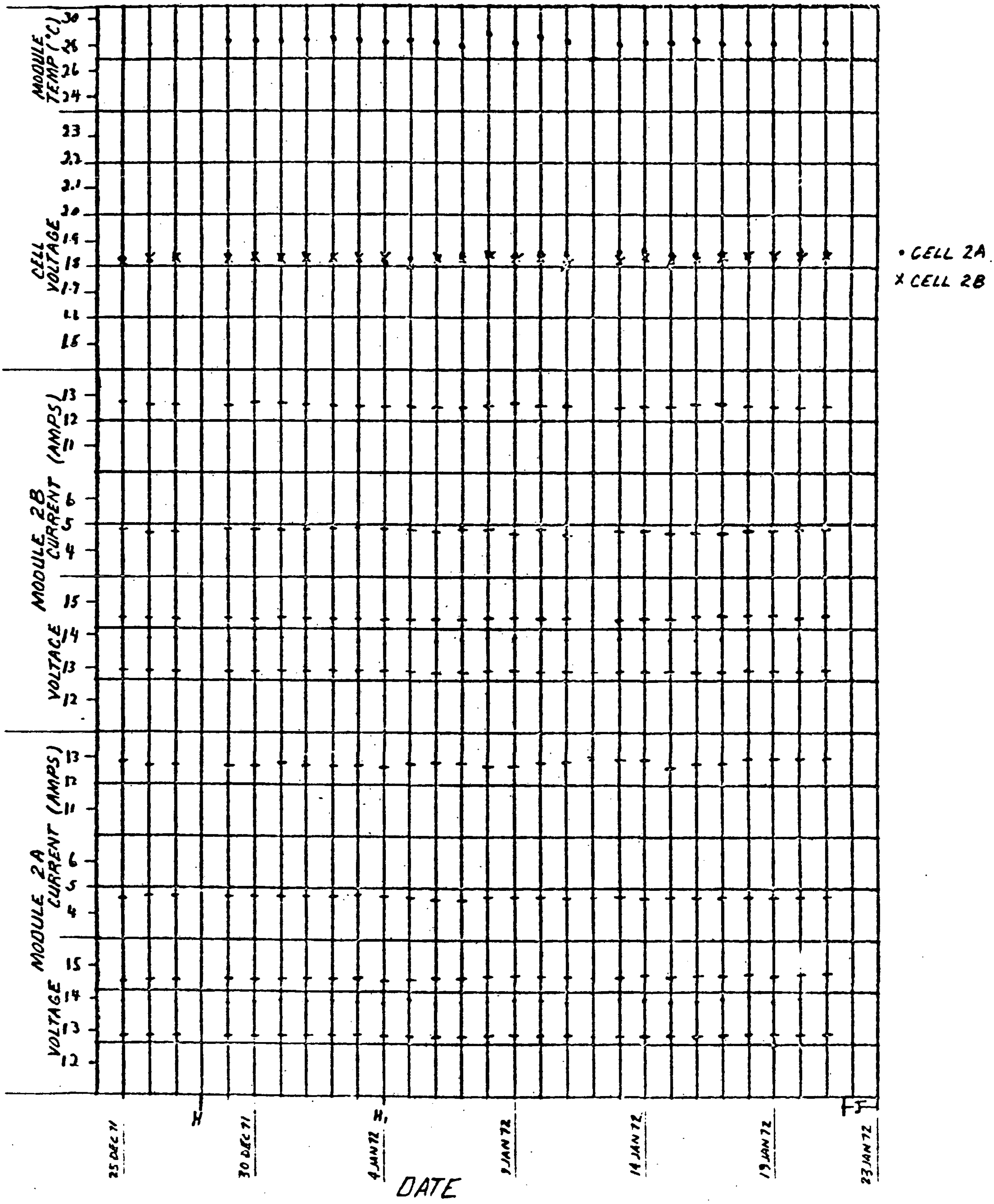


FIGURE 4-81
MODULE 3 SUMMARY PERFORMANCE DATA

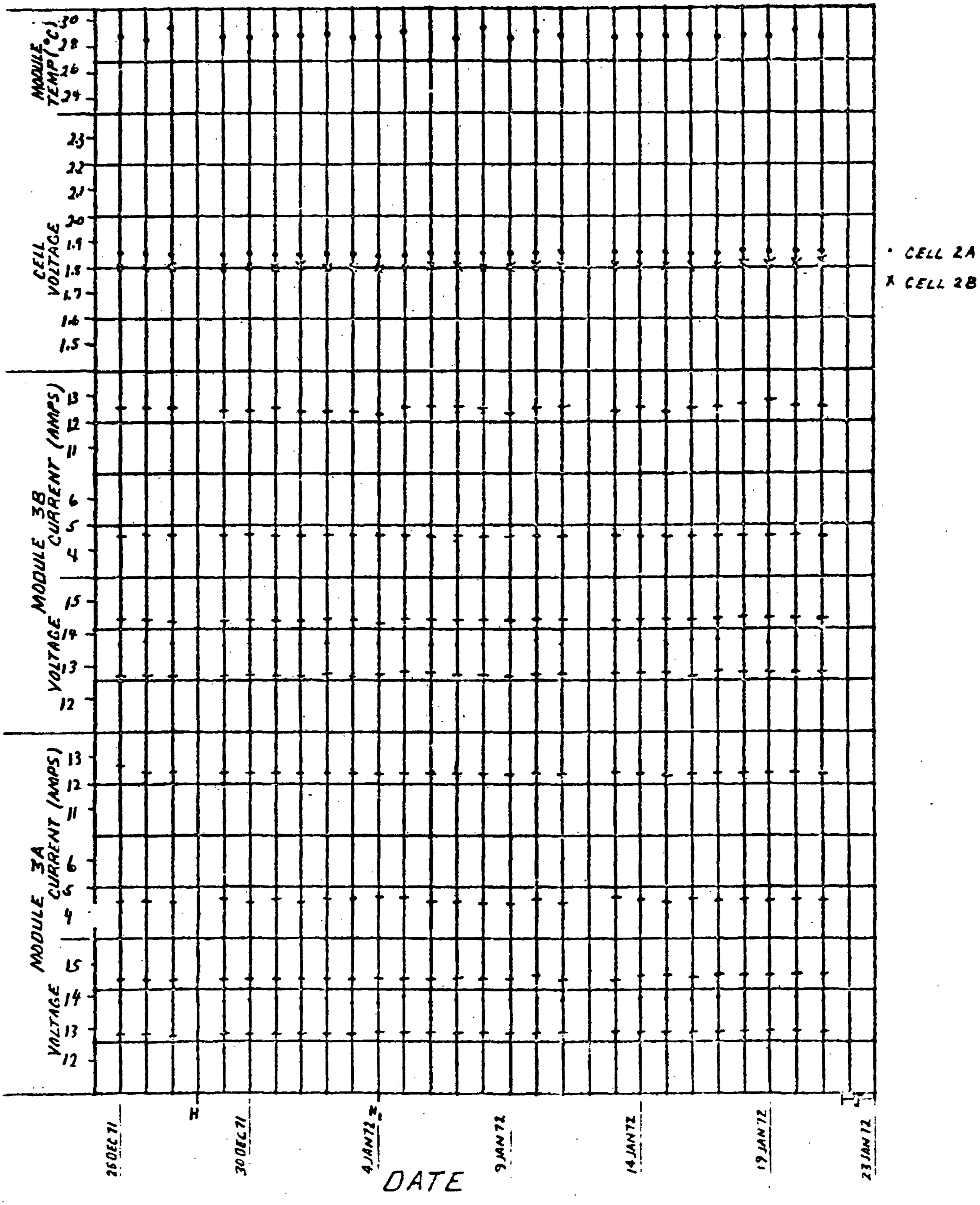


FIGURE 4-82

MODULE 4 SUMMARY PERFORMANCE DATA

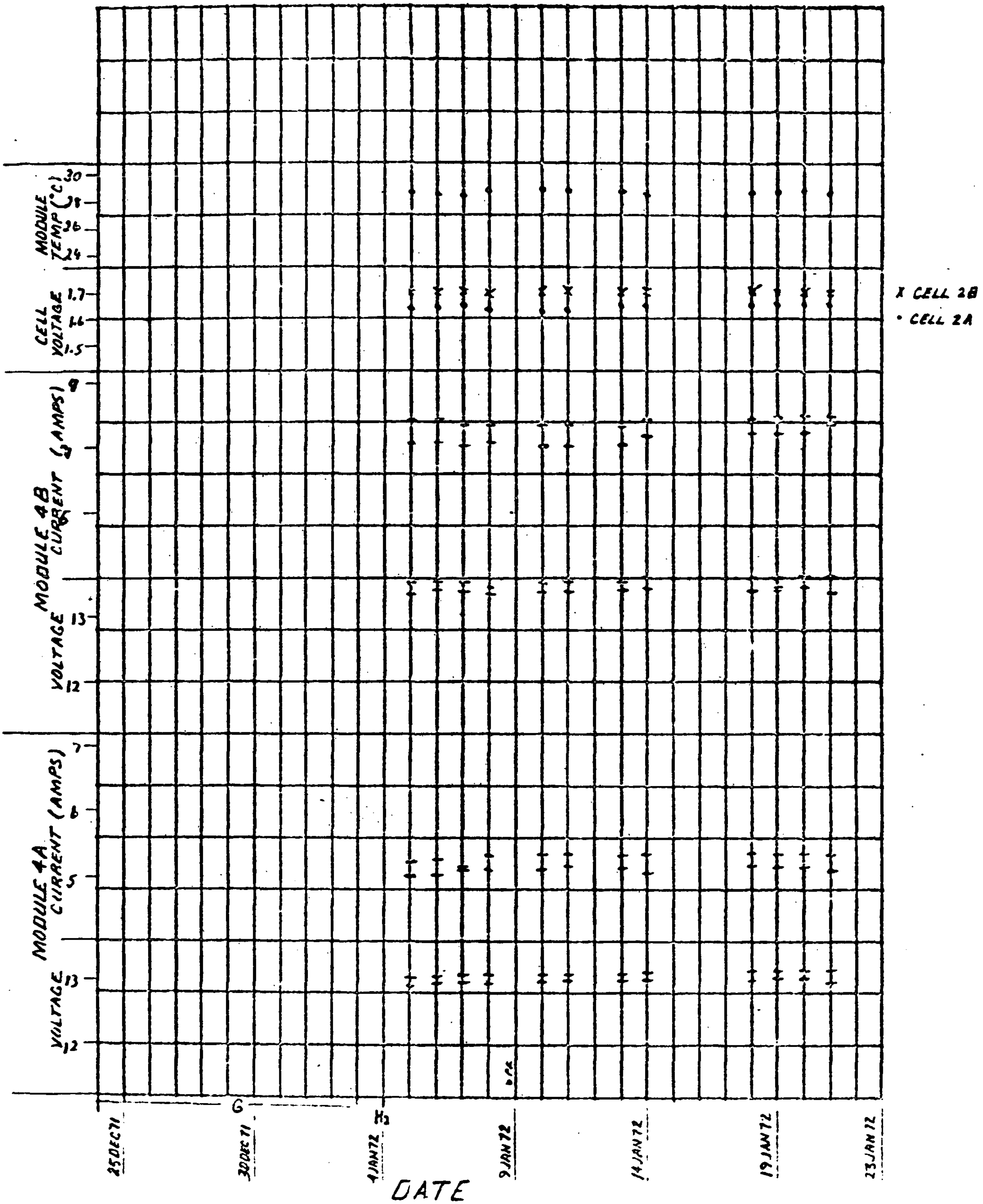


FIGURE 4-83

MODULE 1 SUMMARY PERFORMANCE DATA

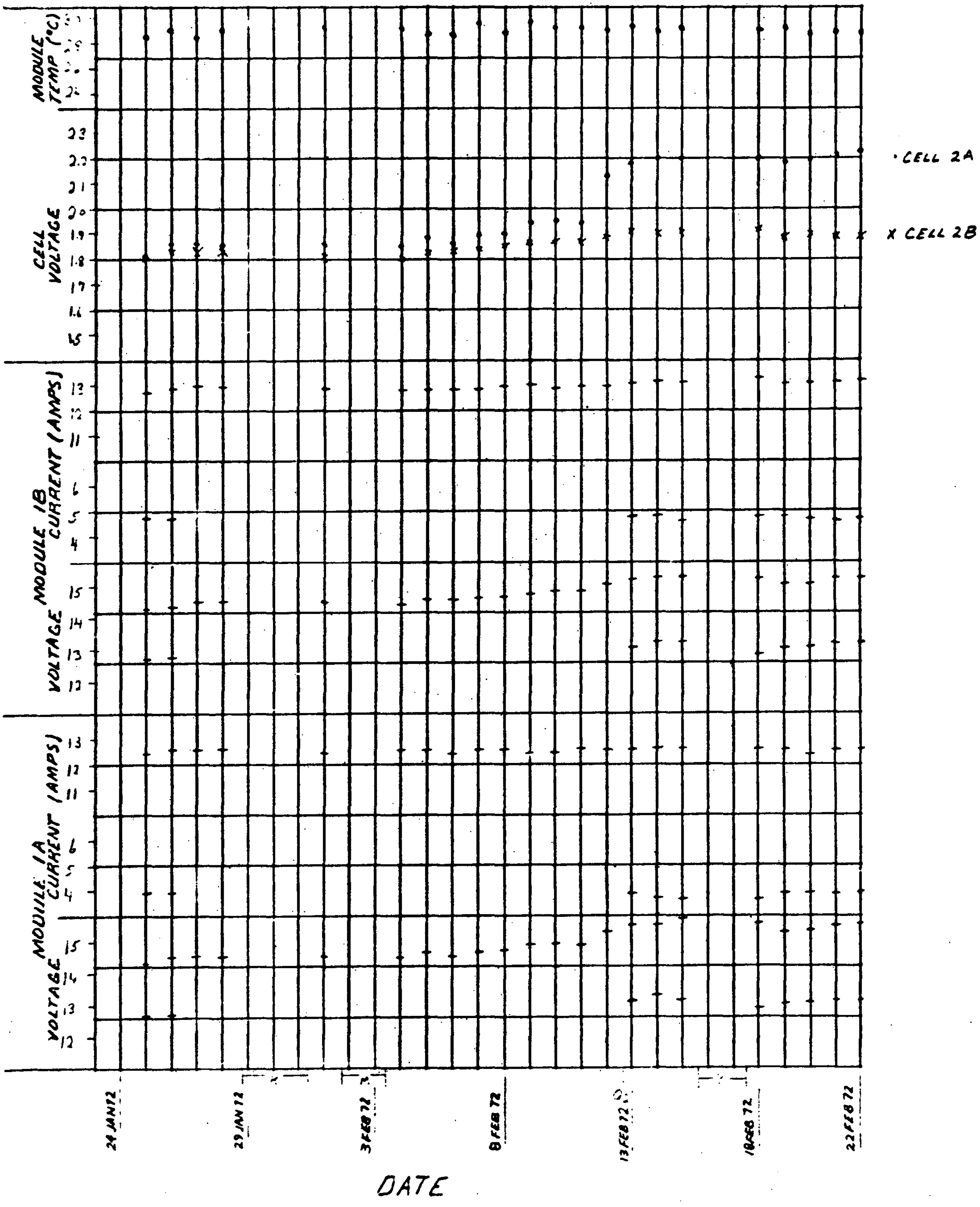


FIGURE 4-84

MODULE 2 SUMMARY PERFORMANCE DATA

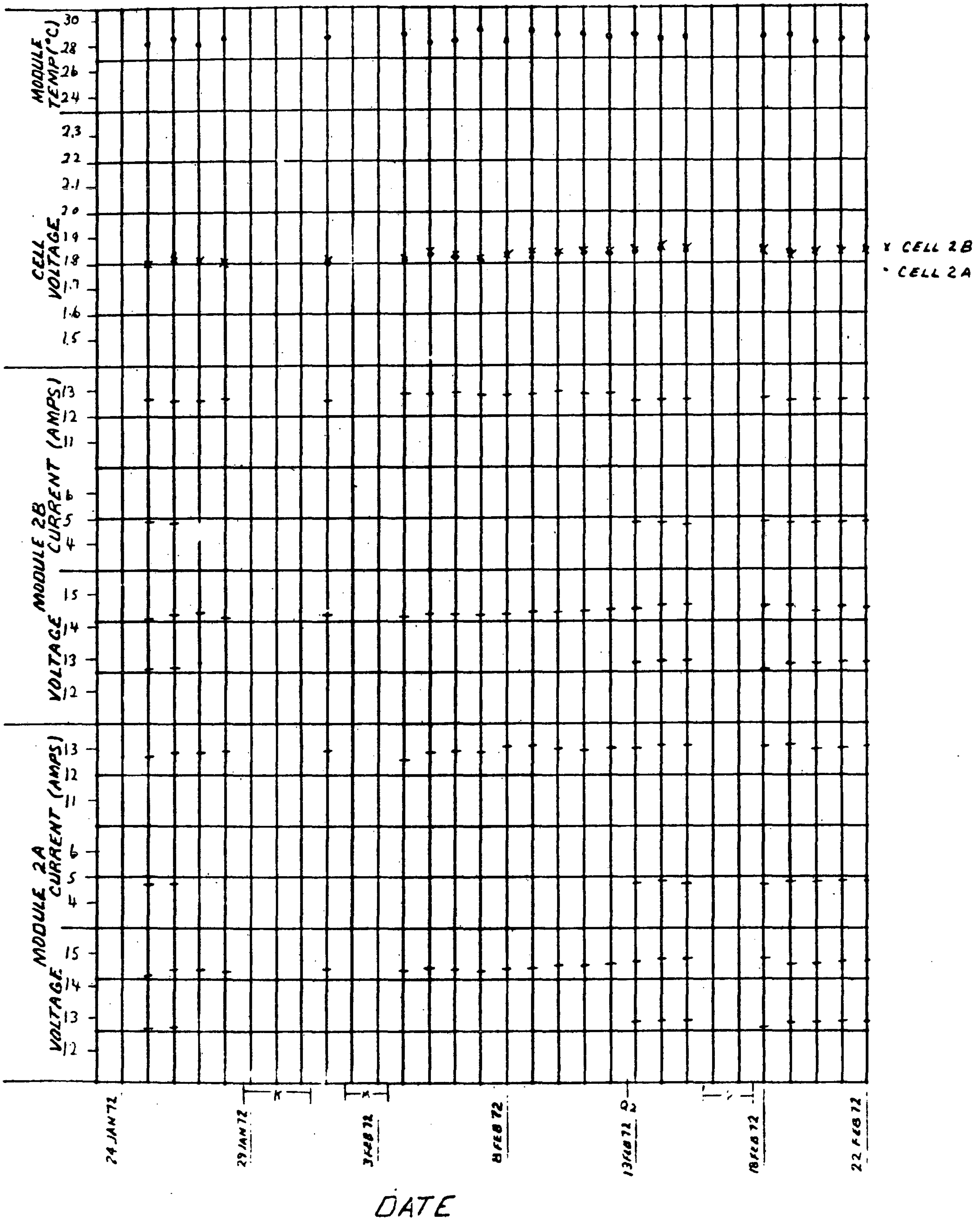


FIGURE 4-85

MODULE 3 SUMMARY PERFORMANCE DATA

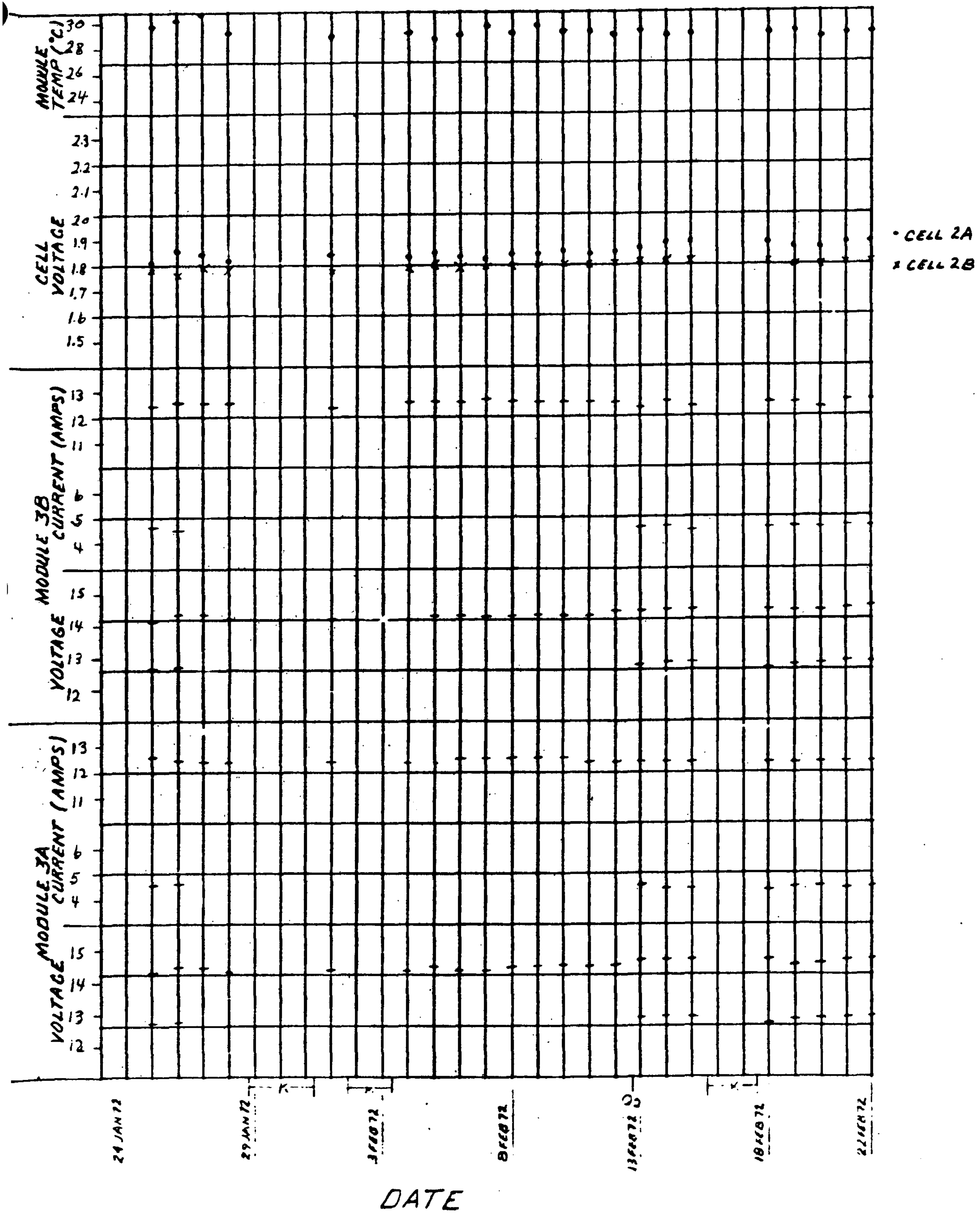


FIGURE 4-86

MODULE 4 SUMMARY PERFORMANCE DATA

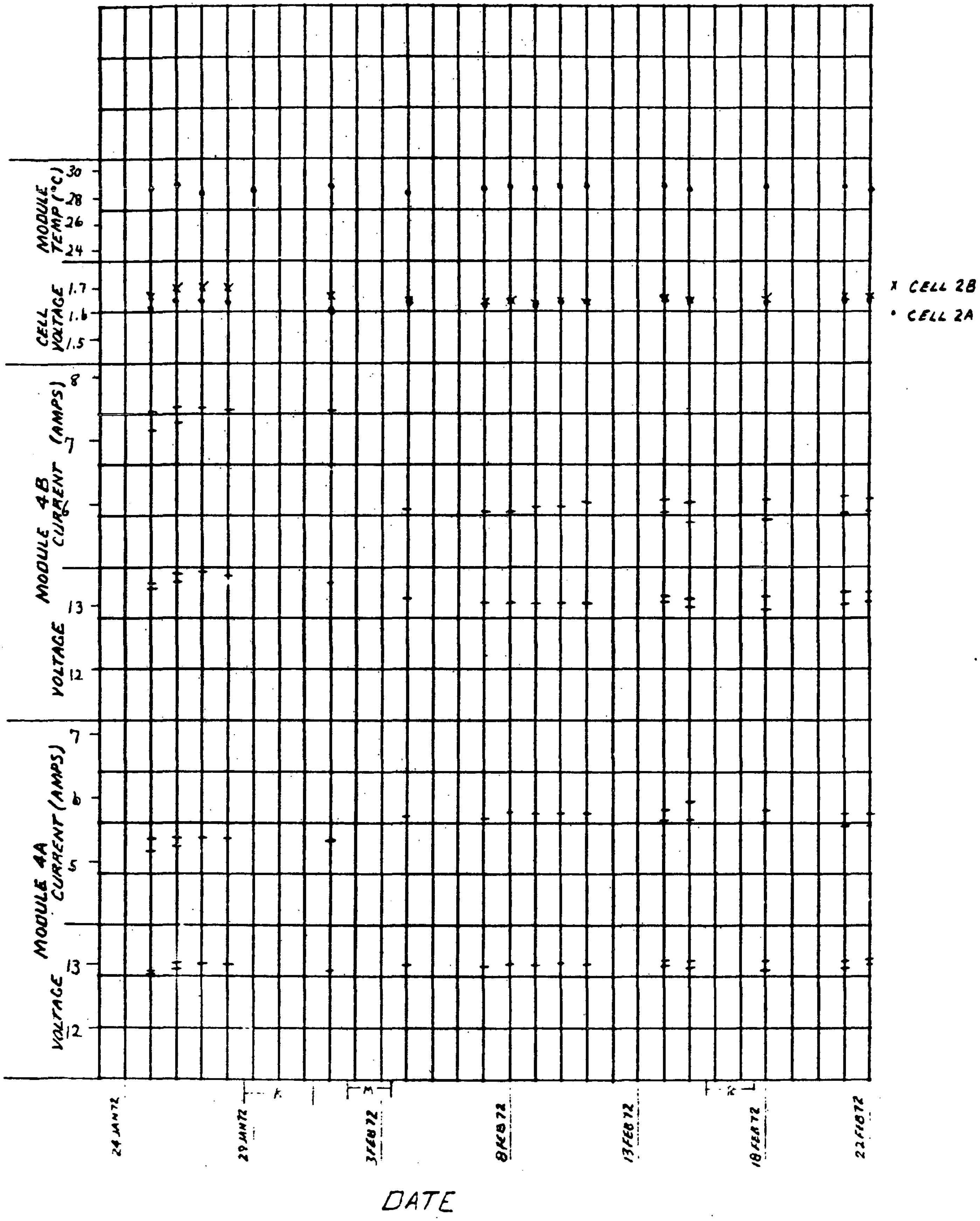


FIGURE 4-87

MODULE 1 SUMMARY PERFORMANCE DATA

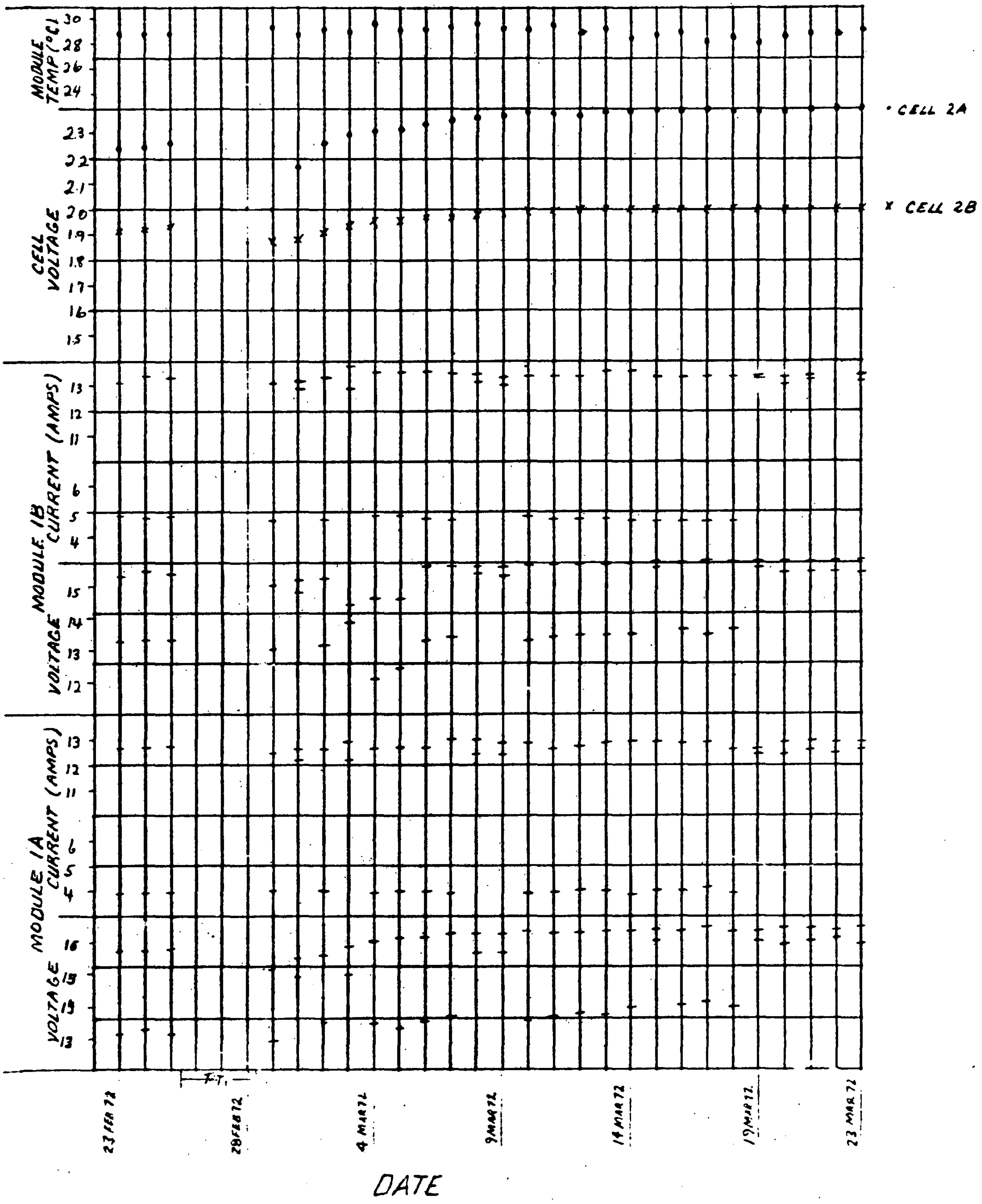


FIGURE 4-88
MODULE 2 SUMMARY PERFORMANCE DATA

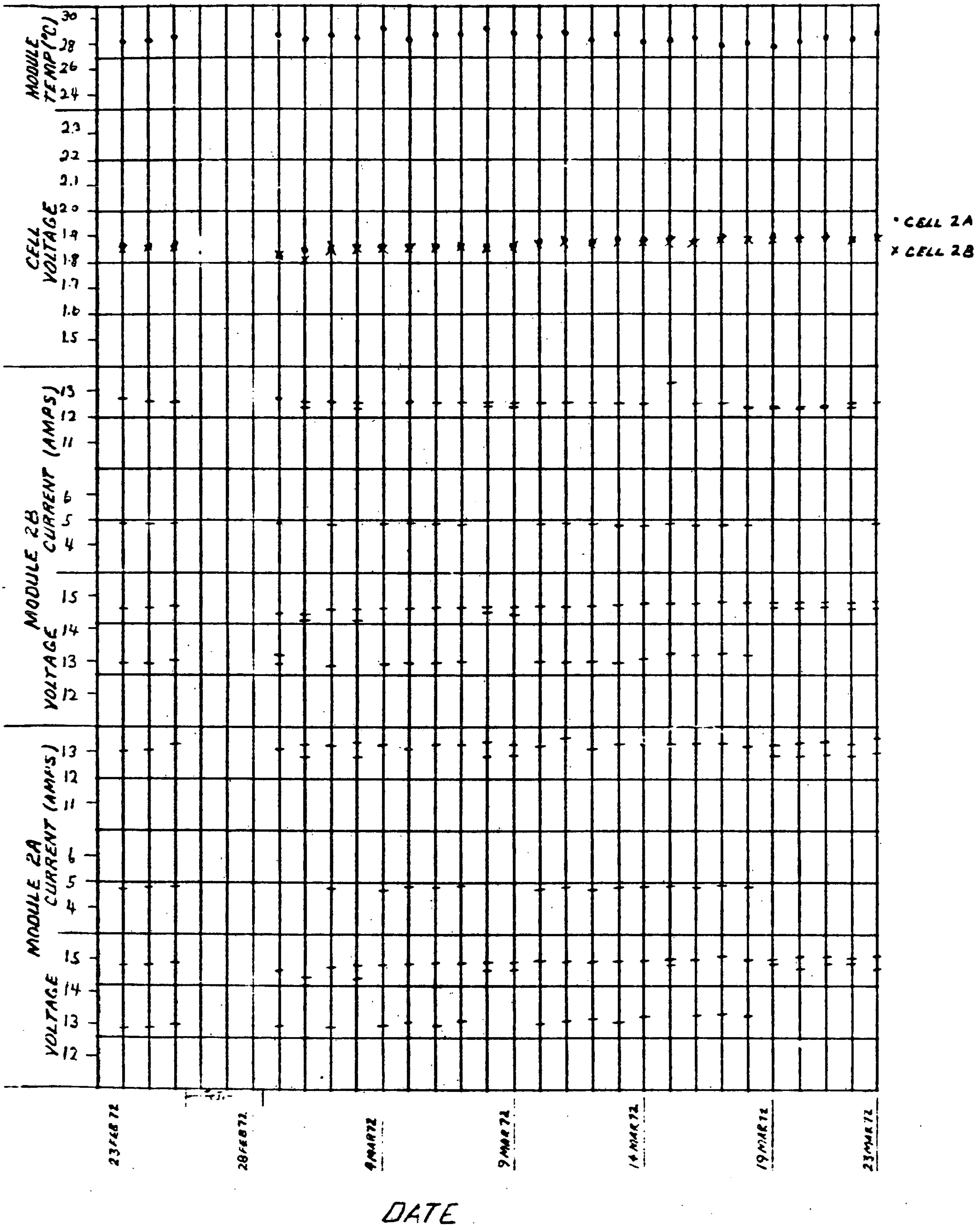


FIGURE 4-89

MODULE 3 SUMMARY PERFORMANCE DATA

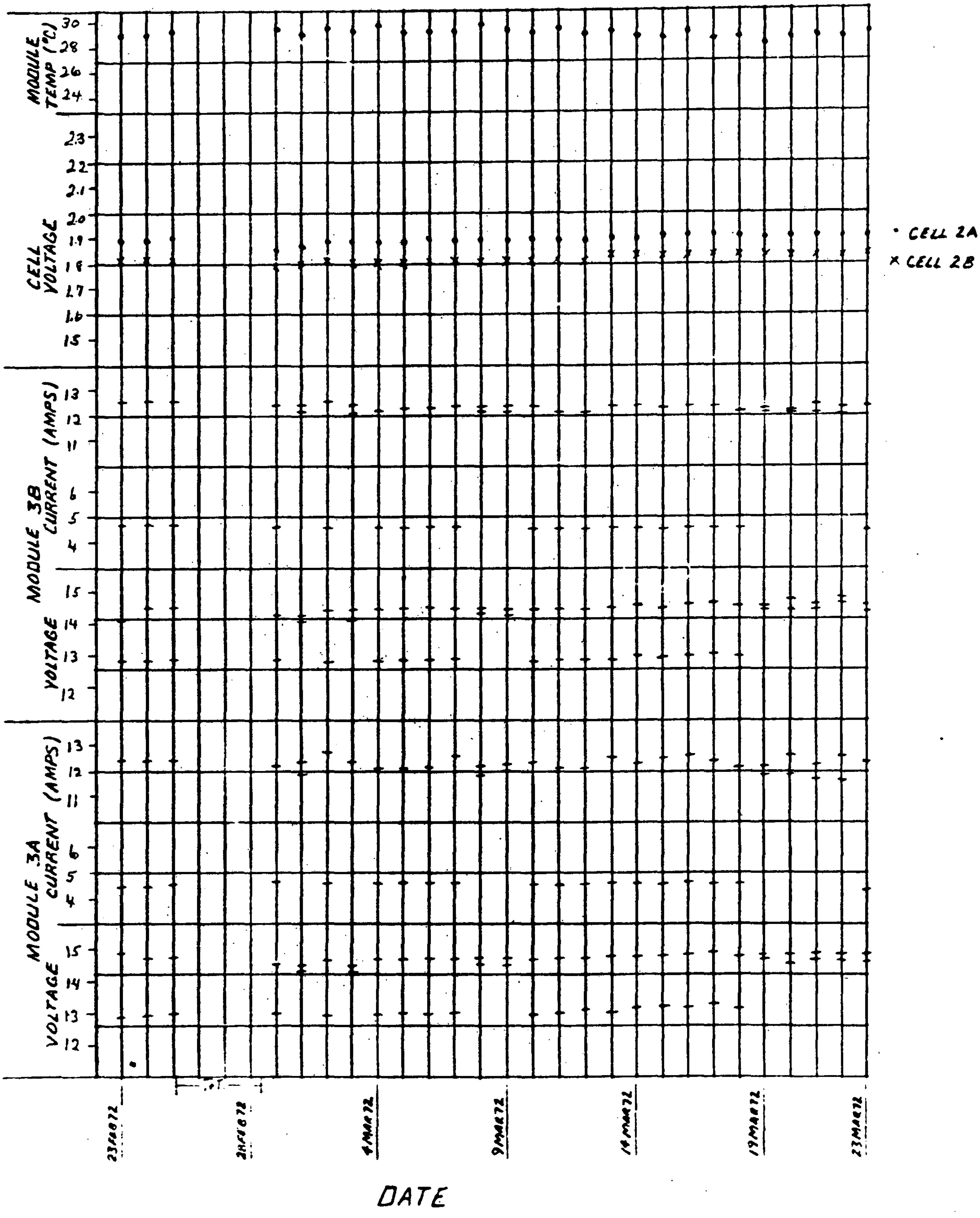
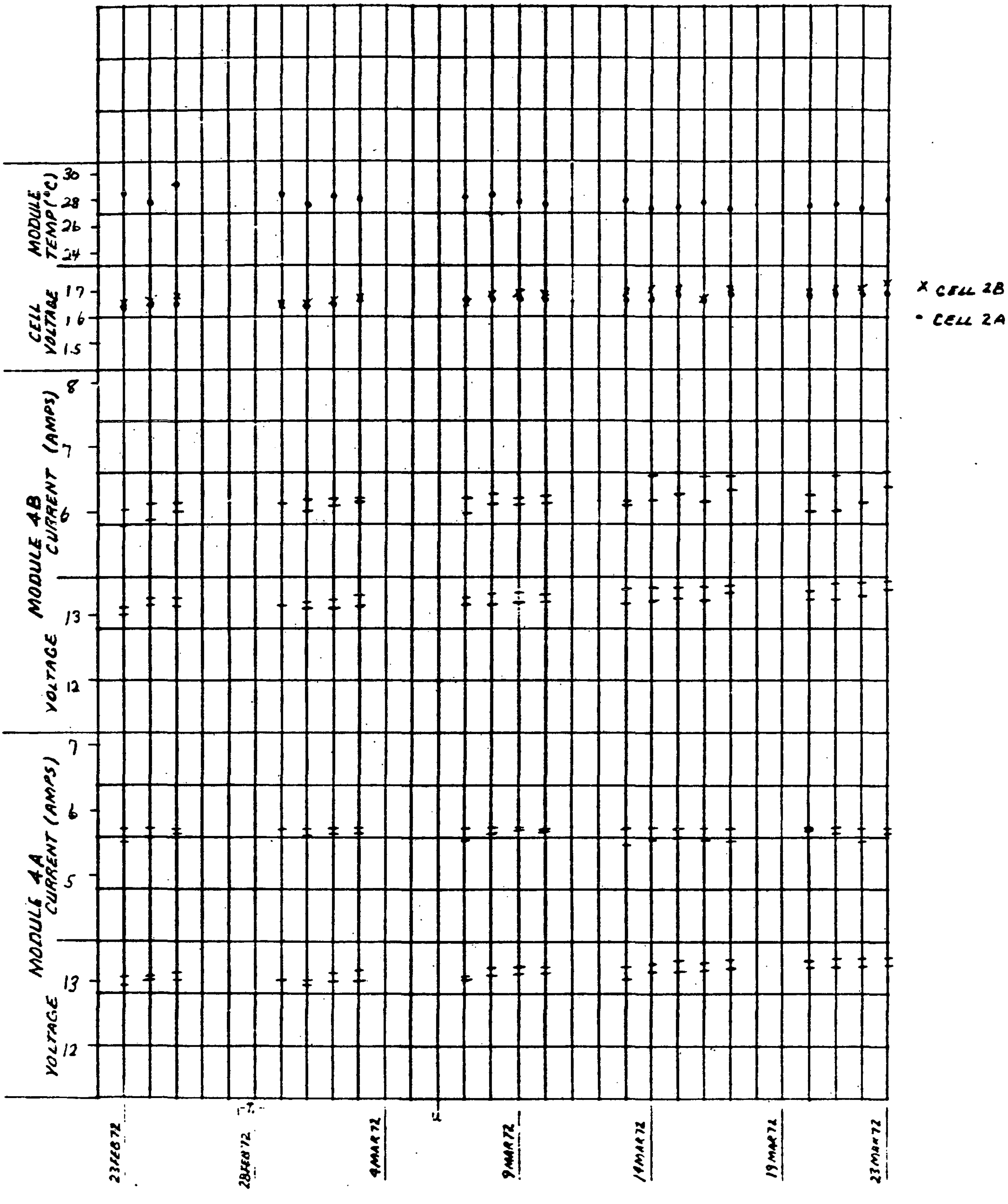
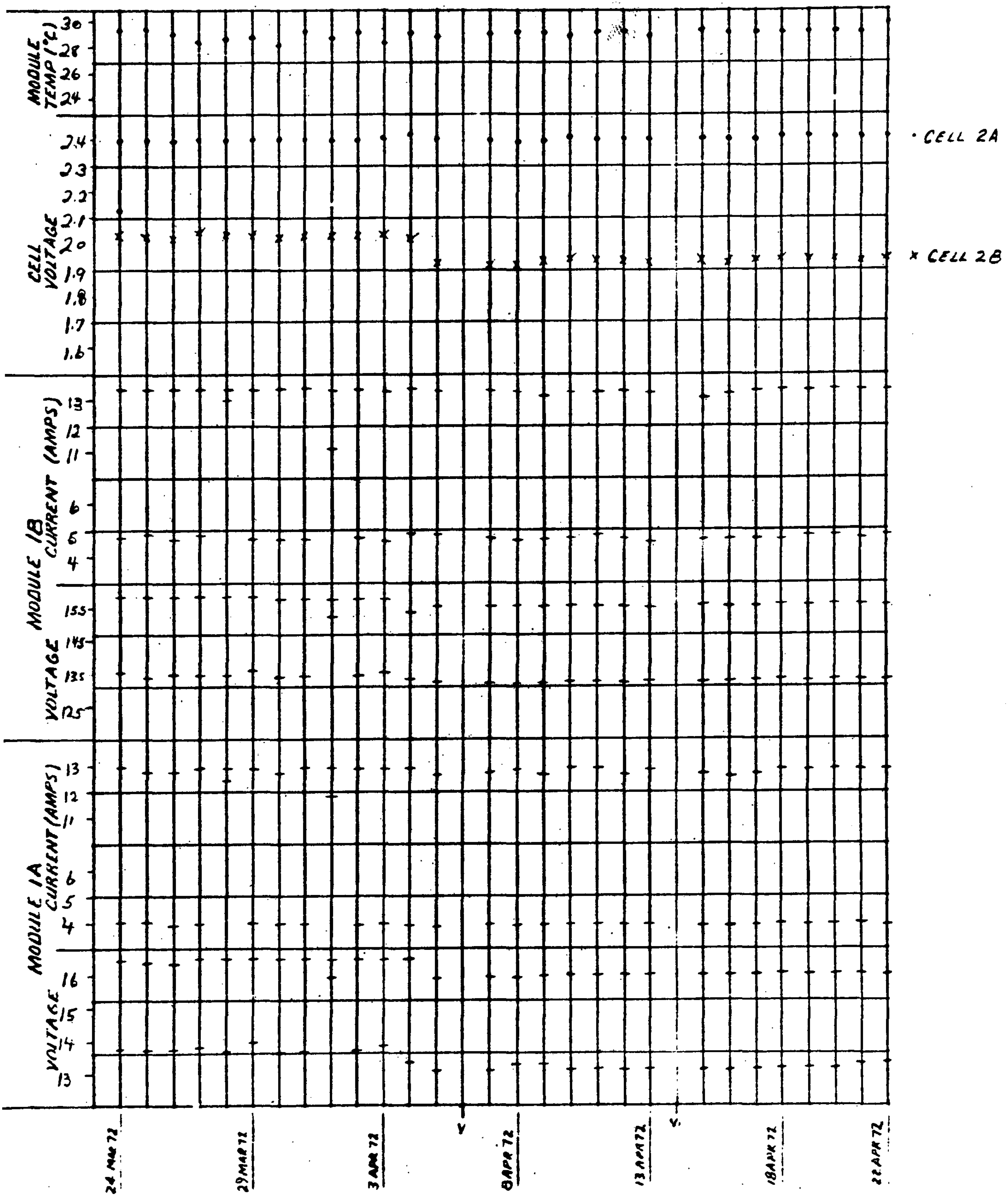


FIGURE 4-90
MODULE 4 SUMMARY PERFORMANCE DATA



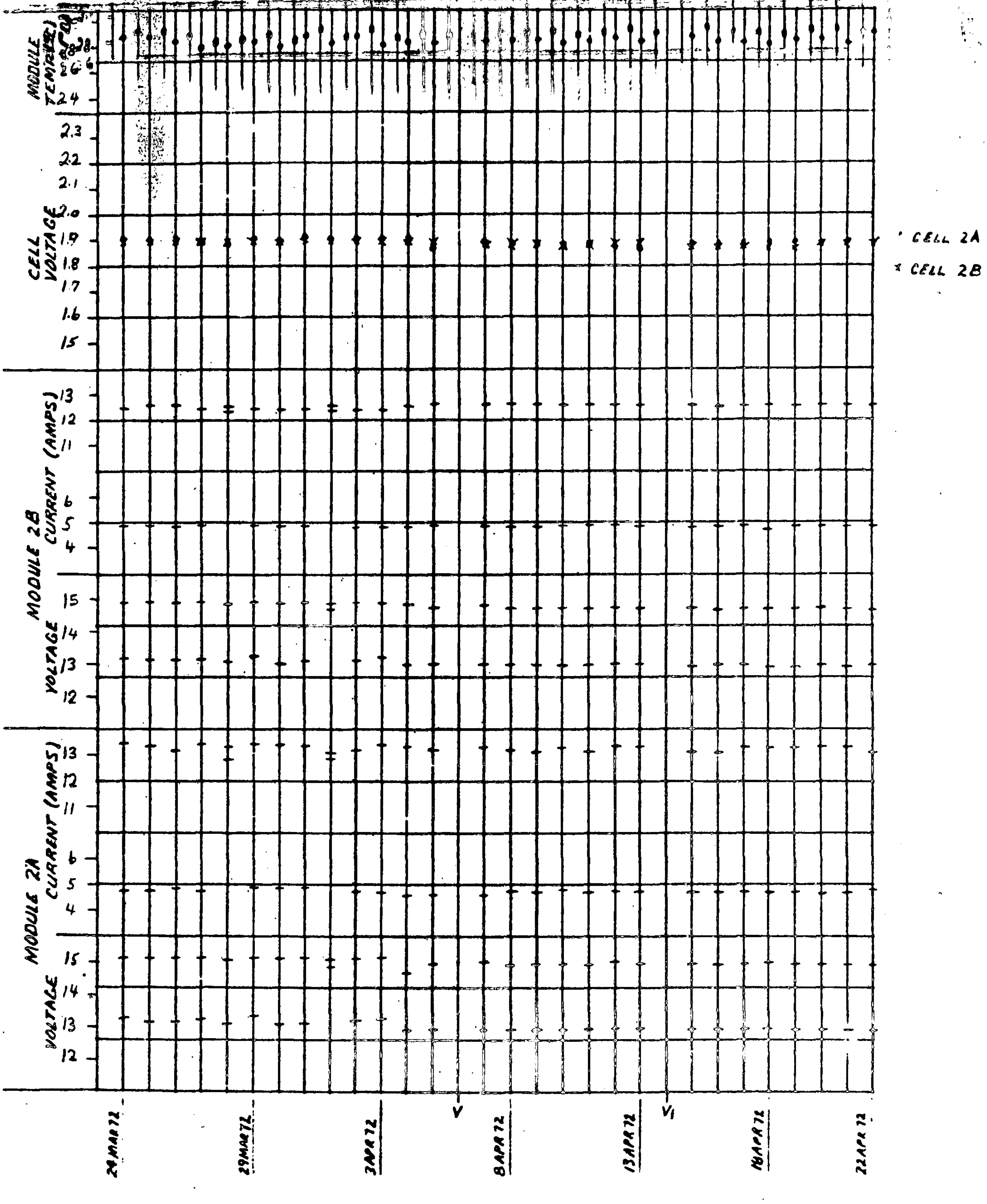
DATE

FIGURE 4-91
MODULE 1 SUMMARY PERFORMANCE DATA



DATE

FIGURE 4-92
MODULE 2 SUMMARY PERFORMANCE DATA



DATE

FIGURE 4-93
MODULE 3 SUMMARY PERFORMANCE DATA

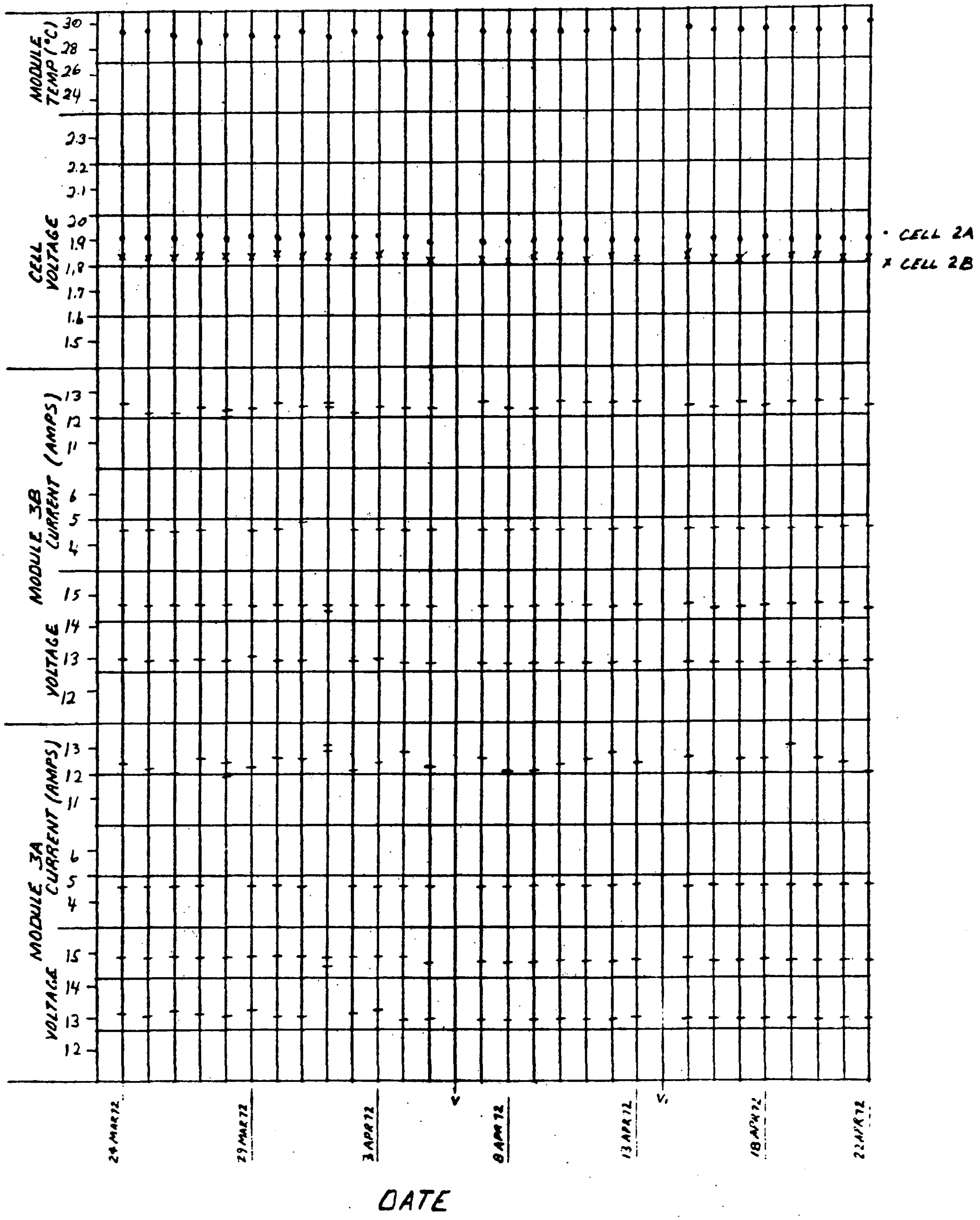


FIGURE 4-94

MODULE 4 SUMMARY PERFORMANCE DATA

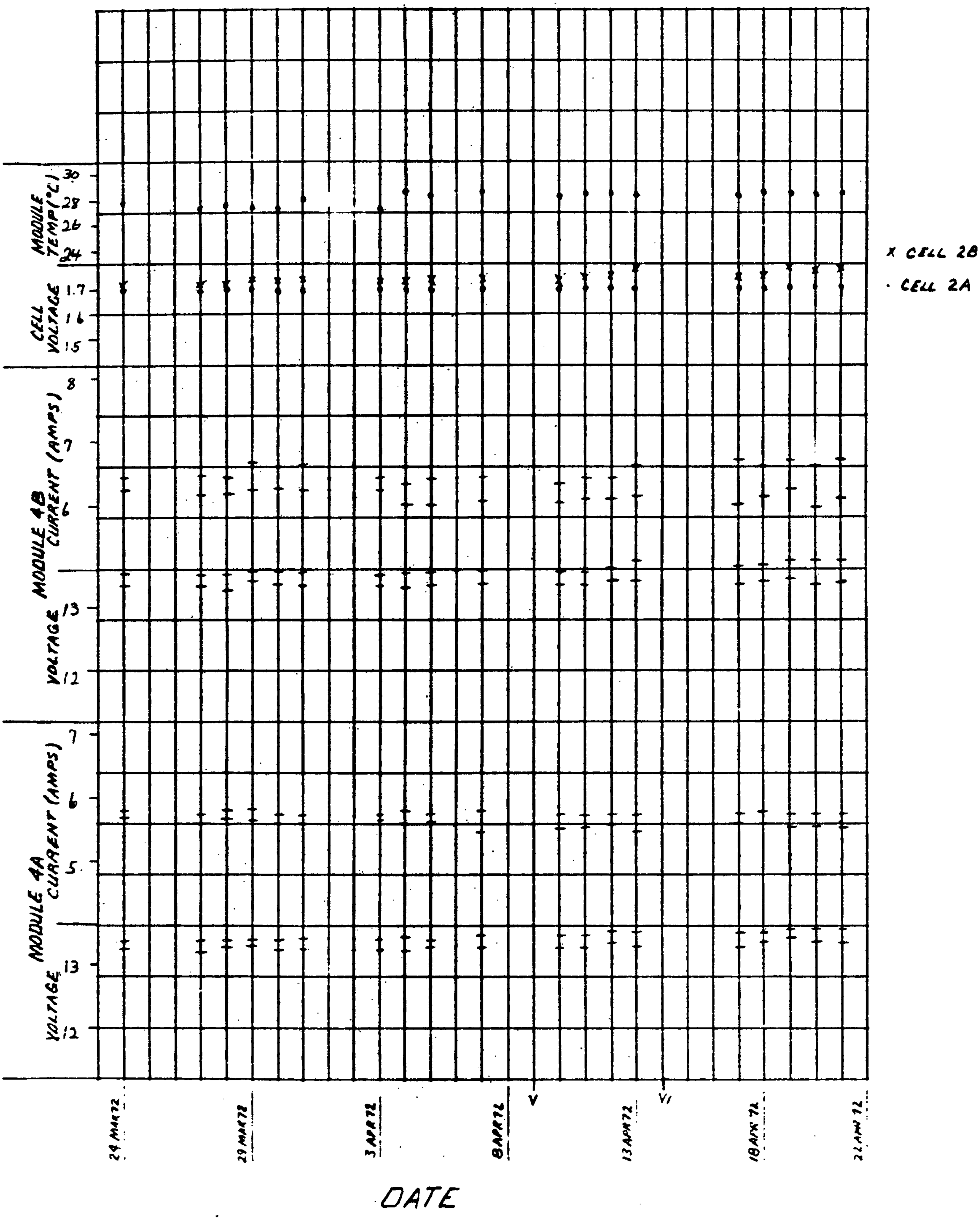


FIGURE 4-95
MODULE 1 SUMMARY PERFORMANCE DATA

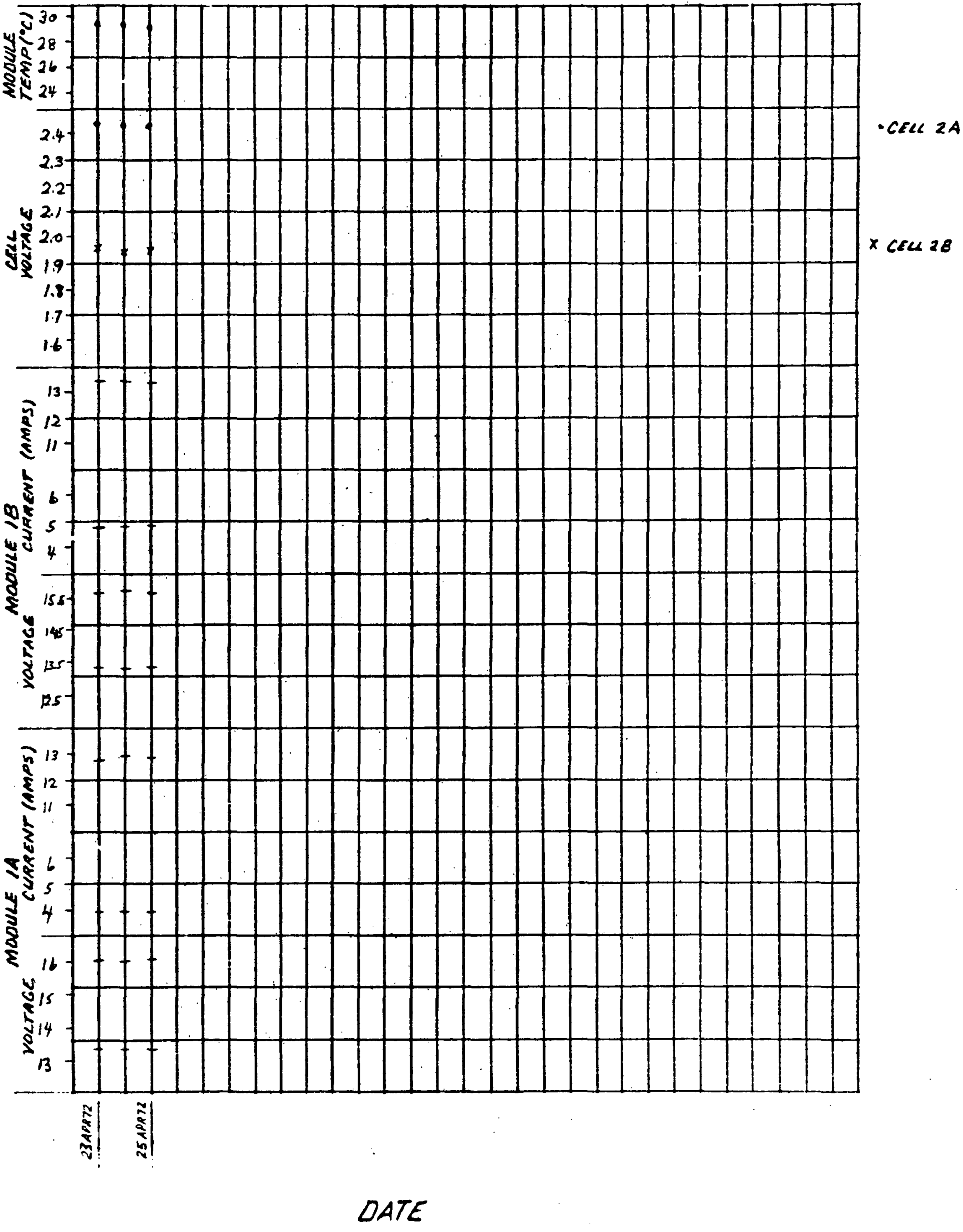
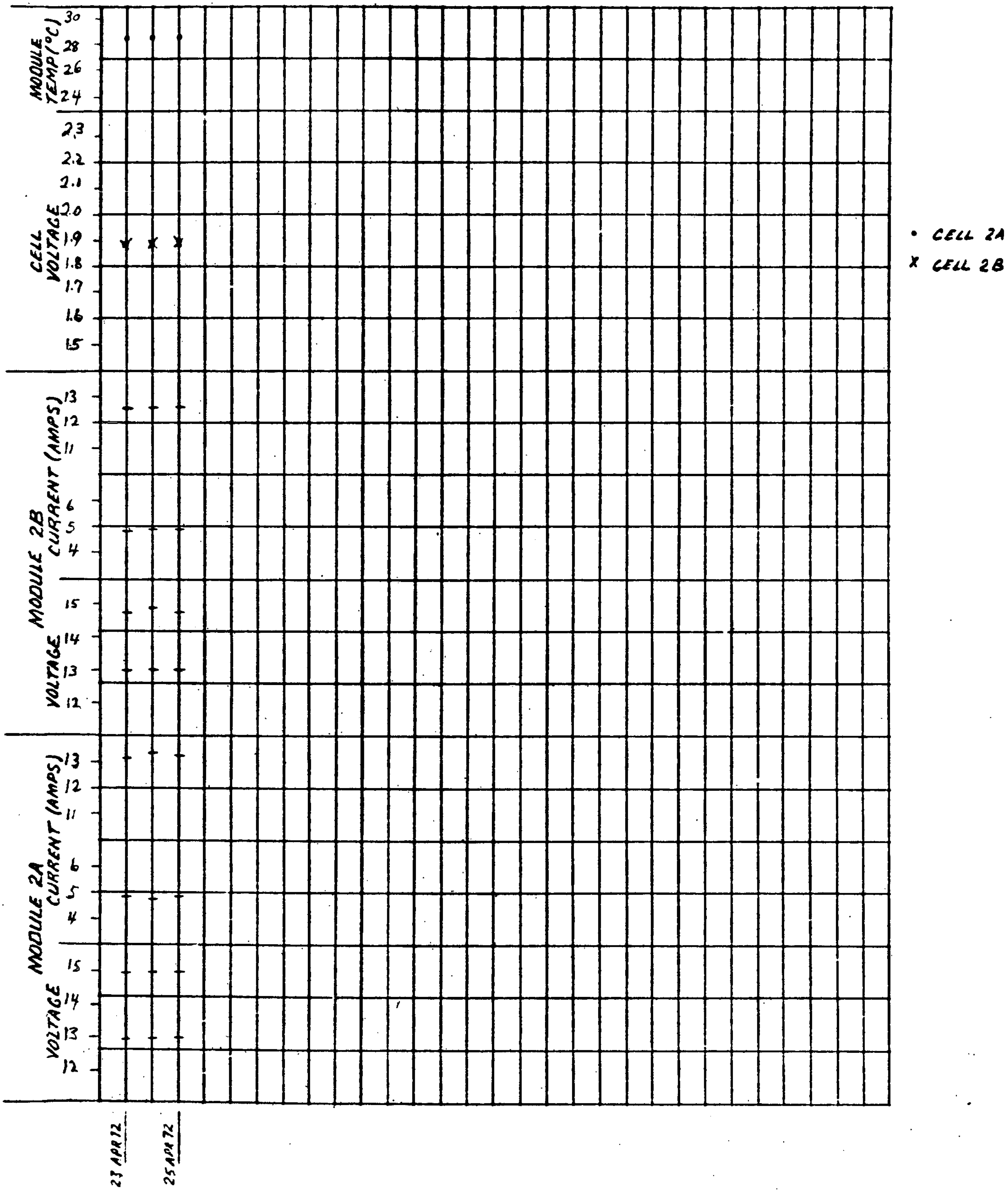


FIGURE 4-96

MODULE 2 SUMMARY PERFORMANCE DATA



DATE

FIGURE 4-97
MODULE 3 SUMMARY PERFORMANCE DATA

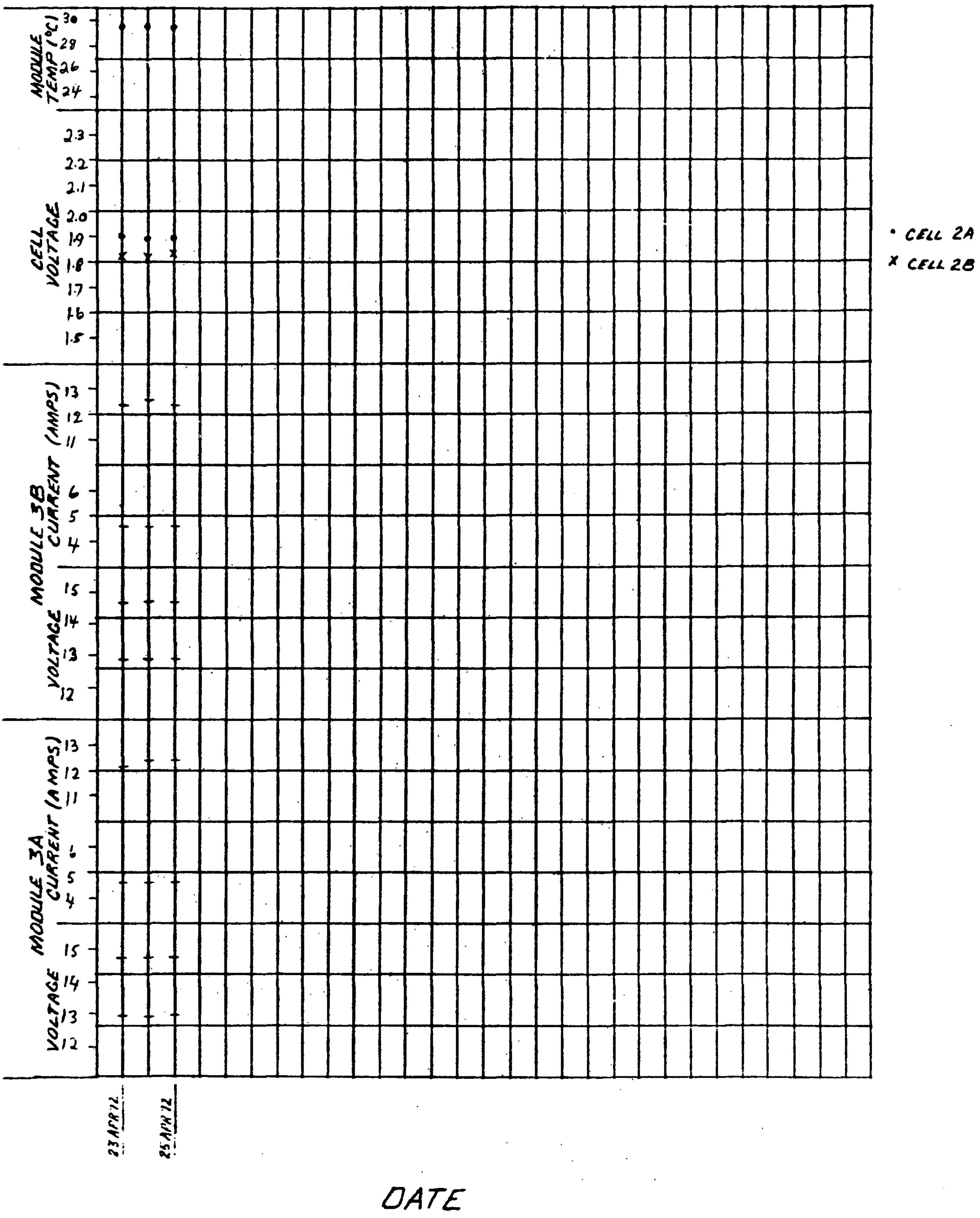
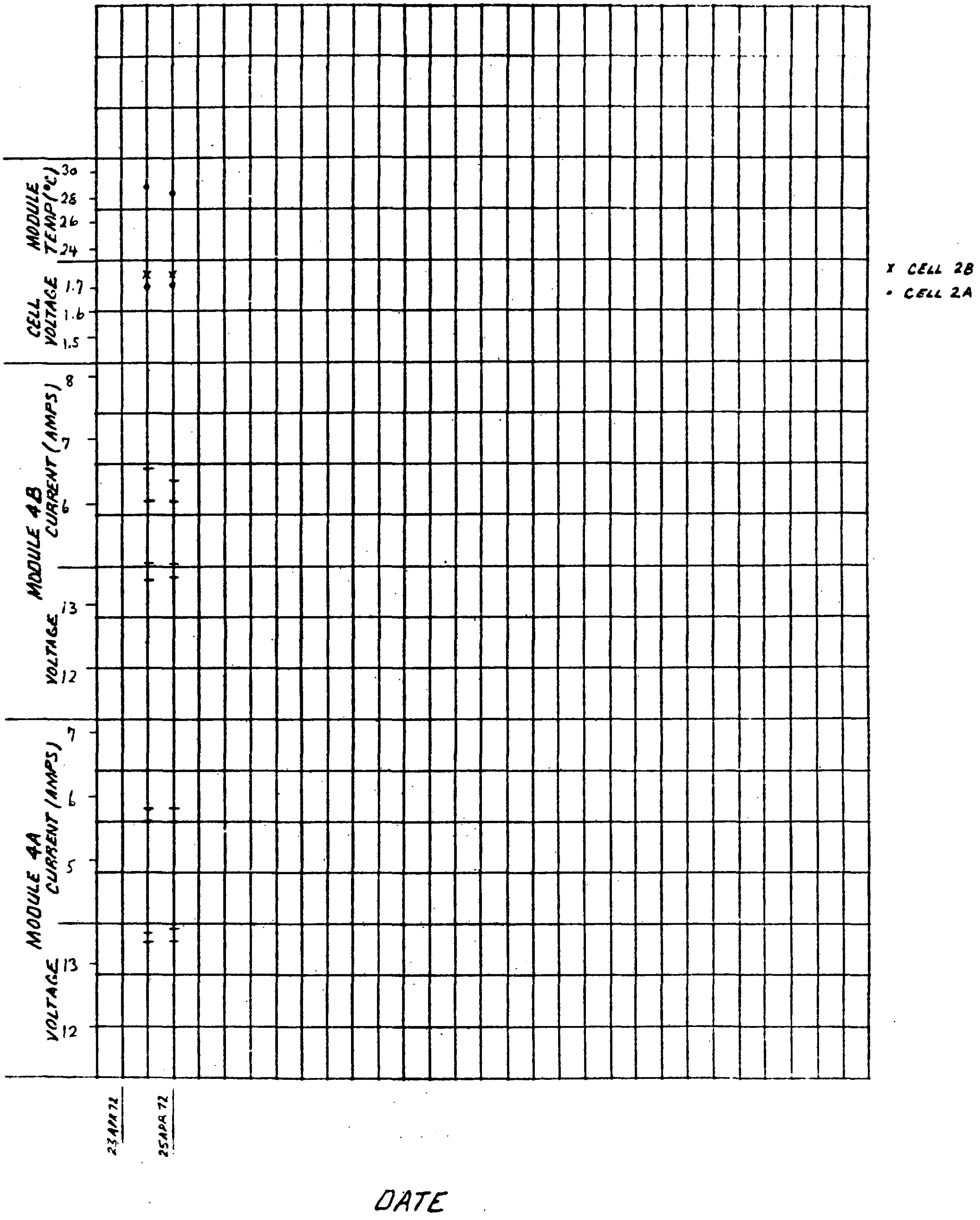


FIGURE 4-98

MODULE 4 SUMMARY PERFORMANCE DATA



4.3.3 Failure Analysis

Figure 4-99 shows the failure history of the CEU as a function of test days. By the end of the testing the CEU had experienced 22 failures. As indicated by the figure, the majority of the failures occurred early in the testing and no failures occurred after 3 March (day 130) thus allowing 53 days of continuous uninterrupted operation.

A total of five failures occurred in the circulating electrolyte unit that were caused by design deficiencies. Three of these failures were caused by broken plastic plumbing fittings in the circulating loop. One failure was caused by a pressure decay, the result of a nonoptimized startup sequence; and one failure was the result of system self-restart in an improper mode after a momentary power loss. All of these design deficiencies were eliminated during the course of the test. The CEU had no cell or module failures during the test. It is judged that all remaining circulating electrolyte unit system failures (17) would have been eliminated by a flight-article quality-assurance program and by the use of high-reliability electronic components.

A summary of the failures that had occurred throughout the test period is shown in Table 4-2. The majority of the system shutdowns were caused by intermittent electronic noise which triggered the master integrated circuit that commanded automatic safety shutdown. The problem was difficult to diagnose because it was intermittent. Circuitry changes and electronic component replacement eventually corrected the problem.

Broken nylon plumbing fittings in the electrolyte loop caused three failures. These were then replaced with Teflon-coated stainless-steel fittings.

An automatic shutdown, caused by low system pressure, occurred during the first segment of the orbital simulation because the startup sequence was not optimized fully. The numerous off-on cycles during orbital simulation made the problem evident. A 10-second electronic delay was added to the nitrogen purge until the oxygen gas production was underway.

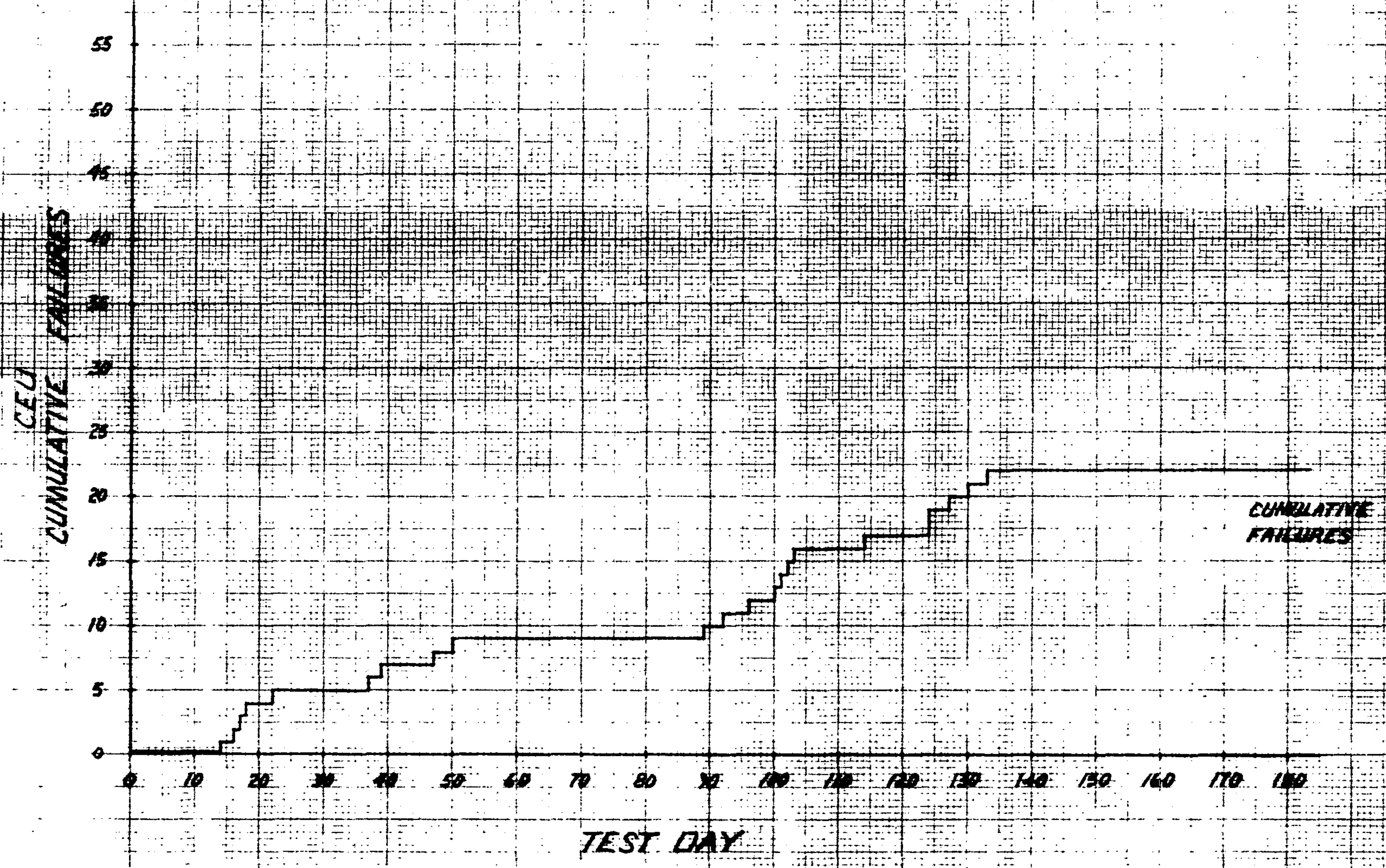


FIGURE 4-99 CEU CUMULATIVE FAILURES

TABLE 4-2
CEU FAILURE SUMMARY

Test Day	Shutdown Mode	Failure Mode	Failure Mechanism	Total Number of Failures	Number of System Failures	Number of Module Failures	Remedial Action Taken
14, 16, 18 37, 39, 47 96	Automatic – various fault indications	False shutdown commands	Electronic noise	7	7		Added filter and replaced I/C
22	Automatic	M4 on during shutdown	False on command	1		1	Manually turn M4 off nights and weekends
50	Manual	No flow thru bubblers	Pressure surge	1	1		Modified vent plumbing
17, 114	Manual	Leak observed	Broken fitting	2	2		Replaced fittings
89	Automatic	Lo system pressure	Broken fitting	1	1		Changed all similar fittings to Cres.
92	Manual	Overheated pump	KOH contamination	1	1		Replaced pump
100	Automatic - no fault indication	False shutdown command	Bad I/C	1	1		Replaced I/C
101	No M4B startup	M4B indicated no current	Loose electric connection	1		1	Tightened connection
133	No M4 startup	M4 failed to start	Unknown	1		1	Cycled switch
102	Automatic	Low system pressure	Pressure surge	1	1		Added time delay circuit
103	Manual	Noise in electronics	Missing filter	1	1		Added filter
124	Automatic	M3 C/B tripped	Failed current regulator	1		1	Installed spare regulator
124	Automatic	False shutdown command	Circuit noise	1	1		Restart
127	Manual	Noise in electronics	Missing capacitor	1	1		Added capacitor
130	Automatic	Noise in electronics	Induced noise	1	1		Added electronic filter

Five problems occurred that did not cause system shutdowns. Module 4 received false "on" commands during a shutdown. The cause of the problem was not identified; instead, the procedure was modified to turn off module 4 on nights and weekends to preclude damage. The module 3 current-regulator card failed and allowed maximum current (as limited by the power supply) to flow momentarily through module 3. This tripped the 20 A circuit breaker and shut down the module. The module 3 current-regulator card was replaced. Erratic module 3 electrolyte temperature readings were noted although they did not exceed the safety limit and did not shut down the system. The temperature probe was replaced when a spare became available. A momentary facility-power failure caused the system to go to a nitrogen-purge mode but did not turn off the electrolysis power to the modules. This action resulted in venting of generated hydrogen and oxygen. The system and facility were modified to provide separate vents for each gas. Module 4 failed to turn on in a few instances. In one case, a disconnected coaxial cable caused the problem. In the other cases, a cause was not found.

4.3.4 Product Gas Analysis

Analysis of product gases from both systems were to be performed as follows: 2 samples on first day, one sample on day 2, 3, 5, 8 and 15 and 1 sample at 2-week intervals thereafter. Due to problems encountered on the SVFU in the early days of testing, gas sampling in accordance with the above schedule, was not performed. The first gas sample drawn for analysis was done on day 9, 3 November 71. The results of that sample and all subsequent samples are shown on Table 4-3.

The H_2 sample on 24 November showed 0.15% O_2 and 1.75% N_2 contamination. This appeared to be air, but repeated samples taken with extreme care repeated the contamination. This type of contamination was also repeated on 8 December, 6 January and 19 January.

TABLE 4-3

PRODUCT GAS SAMPLE DATA

CEU

Test Number	Date	Product O_2			Product H_2		
		N_2 %	H_2 %	Organic	N_2 %	O_2 %	Organic
1	3 Nov 71	N[1]	N	N	N	N	N
2	11 Nov 71	N	N	N	N	N	N
3	24 Nov 71	N	N	2	1.75	0.15	2
4	8 Dec 71	0.1	N	3	0.4	0.07	4
5	23 Dec 71	N	N	5	N	N	5
6	6 Jan 72	0.05	N	N	0.71	0.13	N
7	19 Jan 72	N	N	N	0.3	0.04	N
8	2 Feb 72	0.5	N	N	0.65	N	N
9	15 Feb 72	N	N	N	N	N	N
10	1 Mar 72	N	N	N	0.2	N	N
11	15 Mar 72	N	N	N	N	N	N
12	29 Mar 72	N	N	N	0.1	N	N
13	12 Apr 72	N	N	N	N	N	N
14	25 Apr 72	N	N	N	N	N	N

NOTE:

1 No contaminants detected denoted thus "N".

2 Organic peak at 24.5 minutes. ROM estimated at 1 to 2 parts per million.

3 Very small organic peak at 24.5 minutes.

4 Organic peak at 24.5 minutes. ROM estimated at 1 part per million.

5 No discernible organic peak detected.

On 24 November an organic peak was observed to elute at 24.5 minutes. This was repeated on two samples. Detailed review of system changes between 10 November and 24 November indicated that two Skinner solenoid valves were added to the system. According to LMSC engineers these valves were not cleaned prior to installation in the system. Discussions with Skinner engineering revealed that a Teflon spray and mineral oil are used on various parts of the valves. A new solenoid valve was taken from spares and outgassed for a period of time. Analysis of this trapped gas showed a contaminant eluting at 24.5 minutes, thus verifying that the new solenoid valves were the source of the contaminant.

4.3.5 Bubbler Water Analysis

During the testing measurements were to be made to determine the extent of KOH carryover from the electrolysis system by monitoring the pH change of water in bubblers downstream of the electrolysis units. The schedule called for testing once weekly for the first month and then once every 4 weeks until the end of the test. Table 4-4 shows the results of this analysis. The initial pH of the water in the bubbler was 6.7. At the end of two weeks operation the pH of the water was 10.5 in the O_2 gas bubbler and 9.30 in the H_2 gas bubbler as shown on the table. Both bubblers show a rapid rise early in the test, a leveling off and finally a decrease. This implies that KOH was carried over throughout the duration of the test. The leveling off was caused by the effluent gas carrying KOH out as an aerosol at a rate as great as or greater than was being added to the column by the incomming gas. The decrease in the pH of the O_2 bubbler is probably due to the requirement for draining some liquid out of the bubbler each week. The water level in this bubbler increased gradually and in order to maintain a constant system back pressure some liquid was drained off. Removing liquid also removed some KOH. Based on the decreasing pH value it is apparent that more KOH was removed from the bubbler than was being added to the bubbler by system operation.

TABLE 4-4

PRODUCT GAS BUBBLER DATA

CEU

	Bubbler Water pH Values	
Date	O_2 Bubbler	H_2 Bubbler
9 Nov 71	10.50	9.30
15 Nov 71	10.60	9.25
22 Nov 71	11.40	9.75
23 Dec 71	10.70	9.45
18 Jan 72	11.80	9.50
31 Jan 72	11.85	9.30
15 Feb 72	11.60	8.70
13 Mar 72	11.05	8.70
12 Apr 72	10.50	8.80
25 Apr 72	10.50	8.90

Conversely, the H_2 bubbler looses water on a regular basis and hence distilled water was added to maintain a predetermined level. The H_2 bubbler showed a decrease in pH after 18 January. It is apparent that KOH was being carried out of the bubbler by the saturated effluent gas at a rate faster than the KOH was being replaced by the system operation. The data on the two bubblers implies that KOH is carried over with the effluent gases and that the quantity decreases as system operating time is extended.

A chemical test was performed to determine the approximate amount of KOH that would have to be added to a bubbler to raise the pH from 6.8 to 10.5. The test indicated that 0.09 gram of KOH would be required to raise 1 liter of water the designated amount. The bubblers on this unit contained much less than 1 liter of water, hence the KOH carryover was very small.

4.3.6 Mass Balance Data

Mass balance data was prepared for 18 periods that included all the operating modes of the CEU. This data is shown on Table 4-5. All data on the table has been corrected for standard temperature and pressure. Additionally, the O_2 and H_2 gases produced by the unit have been corrected for water vapor content. Inaccuracies of the wet test meters have been included in the analysis. All calculations were performed in reference to weight in grams. A review of the table indicates some unusual values for current efficiency, total gas to water used, and O_2 produced to H_2 produced. These values can be explained by the following: a) the oxygen wet test meter was very difficult to read and the data was not reviewed or doublechecked at the time the data was taken, b) some inaccuracy in the water weight scale, c) some evaporation took place from the open reservoir, d) liquid drained from the O_2 bubbler was not considered, and e) the liquid level in the wet test meters were not maintained at the proper level 100% of the time.

Table 4-5

MASS BALANCE DATA

Week	End Date	Corrected O_2 Production (grams)	Corrected H_2 Production (grams)	Corrected H_2O Used (grams)	Total Ampere-Hours	Current Efficiency: $\frac{O_2 \text{ Produced}}{\text{Amp-Hr Ideal } O_2}$ %	Ratio: $\frac{O_2 \text{ Produced}}{H_2 \text{ Produced}}$	$\frac{\text{Total Gas}}{H_2O \text{ Used}}$ %
6	10 Dec	16504	2122	19504	7381.82	93.6	7.778	95.5
8	22 Dec	21825	2729	24896	9253.76	98.7	7.997	98.6
9	28 Dec	21764	2711	26771	9458.87	96.4	8.028	91.4
10	5 Jan	21089	3052	28370	11161.72	79.1	6.909	85.1
11	12 Jan	22175	2795	24590	9688.40	95.8	7.933	101.6
12	19 Jan	22222	2769	25329	9815.49	94.8	8.025	98.7
13	27 Jan	17167	2112	19688	7399.07	97.1	8.127	98.0
15	12 Feb	12980	1618	15676	5779.17	94.0	8.022	93.1
17	22 Feb	25365	3129	33589	11131.54	95.4	8.104	84.8
18	29 Feb	15381	1910	17720	6794.64	94.7	8.052	97.6
19	7 Mar	28047	3392	32011	12197.63	96.2	8.267	98.2
20	14 Mar	28198	3587	33194	12315.34	95.8	7.859	95.8
21	21 Mar	27130	3584	31118	12459.09	91.1	7.568	98.7
22	28 Mar	29057	3594	32458	12393.31	98.2	8.083	100.6
23	4 Apr	28832	3561	32810	12335.00	97.9	8.095	98.7
24	11 Apr	22634	2784	25659	9683.97	97.9	8.127	99.1
25	18 Apr	22595	2802	24578	9813.60	96.4	8.061	99.0
26	25 Apr	22564	2799	25749	9484.35	100.0	8.059	98.6

Review of the data indicates that the current efficiency for the CEU is somewhat less than 100%. This can be explained by the fact that all cells in the CEU module had common electrolyte as a result of the circulating electrolyte concept. As a result, every electrode in the module became a cell with every other electrode creating unwanted cells which opposed the electrolysis reaction. This effect was minimized by designing these paths to have high electrical resistance along the electrolyte path between them. The net effect was that a portion of the current delivered to a module was shunted through the common electrolyte and around the electrolysis cells. This shunting reduced the oxygen and hydrogen production to values below Faradaic coulomb equivalents.

The data also indicates that the current efficiency did not change significantly with operating time and that there may have been a slight improvement at higher production rates. Although the difference is not significant considering the data scatter, it does show the correct trend, assuming that shunt current losses were constant and independent of production rate.

4.4 Maintenance

A review of the failures experienced on this unit indicates that all failures were corrected in a relatively short period of time. Access to most electronic circuits was good. Some circuits were added after the basic design for the 90-day test had been completed, thus packaging density for those circuits was high and not readily available for troubleshooting. A redesign would obviously eliminate this problem.

Packaging density and access were also minor faults of the mechanical components. Again it should be recognized that this test program incorporated equipment not originally planned for the unit. Packaging density was high and thus limited access to a degree that a person with large hands and/or normal size tools would have been unable to accomplish all the repairs without removing front components to reach rear components. Small special tools were provided to the resident engineer to assist him in replacing malfunctioning or broken parts. Redesign, with all operations taken into consideration, would eliminate the problem experienced here where parts were added to an existing design.

Several potential maintenance items that could have caused difficulty for anyone repairing the unit include replacing or recharging the ion exchange column, removing and repairing a module or modules, and removing and repairing the reservoir/separator unit. These items and their repair should be considered in future redesigns.

4.5 Instrumentation

The instrumentation installed on the front panel of the unit was adequate for all normal operations and most mechanical fault detection/isolation situations. The instrumentation did not appear to be adequate when electrical noise, or other problems precipitated a mechanical shutdown. A Sanborn 8-channel recorder was used to help isolate some of the causes of unexplained shutdowns. Some of the requirement for additional instrumentation could be eliminated by a flight article quality assurance program and by use of high reliability electronic components. This test program did not impose either requirement on the system.

Certain electronic signals within a given circuit can be used to identify the condition of the circuit. As a concept, if this type of signature were brought out to the control panel and properly displayed, an operator would have a much better indication of the status or changing status of a circuit or circuits. Trouble-shooting time is reduced considerably and impending failures that could cause long shutdowns are frequently eliminated because the proper corrective action is taken before real damage is done.

4.6 Reliability

Section 4.3.3 of this report discussed the number and types of failures that occurred during the testing. It also pointed out that module or cell failures did not occur. Most of the failures were within the electronics circuits and, as was stated in an earlier paragraph, a flight article quality assurance program and use of high reliability electronics components would have increased the reliability of the unit considerably. Even with the 22 failures the system operated more than 80% of the scheduled time and after correcting design deficiencies was able to operate continuously for 53 days. The duration would have been longer but the test period came to an end. The reliability of the mechanical system was improved by the use of Teflon coated stainless steel fittings instead of the plastic fittings. Only 4 mechanical failures occurred, three were by plastic fittings breaking and the forth was pump failure which was caused by a plastic fitting breaking. The use of the plastic-coated fittings was not detrimental to the unit performance and is recommended for future configurations of the system.

The only unresolved failure was the cause of module 4 attempting to restart after being shutdown. Whether this presented a hazard or safety concern to personnel or equipment cannot be determined until post-test analyses, if conducted, identify the problem. Presumably, the problem was in the module 4 circuitry. In order to gain as much system operating time as possible, module 4 was operated during normal working hours only and turned off during weekends and at night. Detailed trouble-shooting was not conducted to isolate the problem.

4.7 Hazards and Safety Concerns

Only two situations existed within the operation of the CEU that could be considered hazard and safety concerns. One was the attempted restart of module 4 after shutdown as has been discussed in other paragraphs. The second was the discharging of both oxygen and hydrogen through the same vent line while the system was operating. This occurred when a momentary power failure allowed the purge solenoid valves to close, thus permitting all generated gas to vent overboard collectively rather than pass separately through their respective bubblers. This problem was eliminated by installing completely separate vents for each gas.

Other hazards or safety concerns that were reviewed pertinent to the CEU include: environmental extremes exceeding personnel and equipment tolerances, energy sources, electrical overload, electrical shock, inadvertent actuations, current limiting and other safety devices, fire suppression, toxicity, biological growth, caution/warning devices, time constraints, emergency procedures and power source failures. All of these items were adequately covered by the existing design except possibly the use of flammable materials within the unit and the toxicity of some materials in closed environments. The use of absorbent material to help contain leakage in the base of the CEU system structure was extremely useful in the 90-day manned conducted in 1970. It was not used in this test and would have been useful on two occassions when plumbing fittings broke and allowed electrolyte to leak out.

4.8 Interface Requirements for Spacecraft Applications

Based on the testing experience gained in conducting this 26-week test program, certain interface requirements presented themselves as desireable changes should the CEU be selected for spacecraft applications. None of the suggested changes are to be considered negative comments as it is recognized that the system as presently configured was not designed for spacecraft applications but was designed for special terrestrial testing. These suggested changes are as follows:

- Reduce the requirement for multiple power supplies. Presently the unit requires 3 power sources. It is suggested that the complete system be modified to require only one power source and that the power requirements be identical to that available in the spacecraft. Along with this change it is suggested that the system be made less susceptible to power supply ripple and rigid regulation.

- Presently the systems circuits contain an excessive amount of circuit noise. This noise should be reduced considerably for spacecraft applications.

- One of the major changes to the system will be to make it operable in a null gravity environment. Gravity flow meters will have to be replaced as well as the gravity type reservoir. The reservoir presently serves as a liquid-gas separator, as a reservoir, and as a mixing tank for electrolyte and the water supply. Replacing this reservoir will be a difficult task but one that is necessary for aerospace applications.

- Some of the hardware used in the construction of the system does not meet space vehicle requirements specifications. Replacing non-compatible equipment with compatible equipment and flight qualifying the system may change its performance characteristics considerably.

- During the recent tests (90-day and 182-day) the unit was not operated at any significant internal pressure. Spacecraft applications may require discharge of product gases to an accumulator. If a compressor is used for pressurization of the gases after leaving the unit, an undesirable parasitic power penalty is encountered. If the system is operated at or slightly higher than accumulator pressure, leakage of system electrolyte is likely to be encountered. This system was not operated at accumulator pressure in either previous test. During the 90-day test, where the system back pressure was 9 psig, some seepage of electrolyte from between cells was evident. With less than 1.5 psig back pressure, as was the case in the 182-day test, there was no evidence of electrolyte seepage from between the cells.

- The system should be modified to be compatible with the onboard checkout system of the space vehicle. This was partially done in this test program in that parameters were recorded, monitored and displayed remote from the unit. Additional channels of data, relative to status of electronic circuits, should be brought out of the system for remote monitoring and display or perhaps be designed to allow "self-check".

- An interface heat exchanger unit had to be installed between the CEU and the cooling source in both the previous tests. In both tests the problem was a heat exchanger that was not capable of withstanding the coolant system pressure. It is suggested that this requirement be eliminated and that all components of the cooling system within the CEU be made compatible with the vehicle's cooling system.

- Some special tools were required for repairs within the CEU. These were special in the sense that the handles were very short or longer than usual to reach areas not accessible with normal tools. This requirement should be eliminated in an effort to minimize the quantity and types of repair tools that must be carried on a space vehicle.

- Related to the special tools problem is the problem of maintainability. Although all maintenance was accomplished during the testing, it would have been easier if the packaging density had been lower. This would also have eliminated the requirement for special tools. A large person or a person in a space suit would have had a difficult time trying to make certain repairs on the unit.

- The problem of not being able to remove one module while allowing all others to continue operating was not encountered in the 182-day test. However, it was encountered in the 90-day test and should be incorporated in future designs. The present design

3

does allow securing and isolating a malfunctioning module but it does not permit removing the module for repair or replacement. The use of an installed spare, such as module 4 was in the test, is good but if a second module fails, as it did in the 90-day test the unit has to be shutdown to remove and repair the modules which may be undesirable on a long mission of a fully integrated system. Also, being able to remove a module and allow other modules to operate permits gas generation at a reduced level rather than at a zero level. At a reduced level of operation some O_2 is being replaced, some H_2 is available for the CO_2 reduction system and hence only one system is partially shutdown rather than 2 or more systems completely shutdown.

- Nitrogen consumption during the test program was considerable and would present an undue penalty to a space vehicle. This penalty could be reduced considerably if the N_2 were recycled after an initial purge of the unit had taken place. After a predetermined period of purge and after analysis of the effluent gas for O_2 and H_2 content, the N_2 could be recycled back through the unit rather than dumped overboard.

- Twice during the 182-day test plumbing fittings broke and allowed some quantity of KOH solution to spill out. If this happens in a space vehicle in null-gravity a major contamination problem will exist for the crew and the contaminant control system. Therefore a method of KOH containment is suggested to: 1) minimize the amount of KOH solution that can leak out should a fitting, line, cell, etc. break and 2) provide an internal self-contained blower/filter system and absorbent pads to collect the leakage before it can escape the envelope of the electrolysis unit.

5.0 STATIC VAPOR FEED UNIT TEST RESULTS

This section presents material on the test preparation, testing and post-test analysis of the static vapor feed water electrolysis unit. The data is presented in narrative format from the start of system refurbishment of the 90-day manned test in a space vehicle simulator, through acceptance testing, system checkout, and finally through 26 weeks of performance/endurance testing. Included in acceptance testing will be data collected by Allis-Chalmers Manufacturing Company (48-hour tests) and Life Systems Incorporation (LSI) (100-hour tests). LSI also performed development type tests on individual static vapor feed unit cells.

5.1 System Refurbishment

Operation of the static vapor feed unit preceding and during the 90-day manned test indicated that changes were needed to improve the performance of the system for future testing. The refurbishment discussed below was accomplished at the McDonnell Douglas Astronautics Company facilities under the sponsorship of Independent Research and Development funding. As part of the refurbishment the original manufacturer performed tests on cells and modules and replaced unacceptable parts. All 5 modules were disassembled and diagnostically tested for pressure drop and voltage level at specific operating conditions. Too high a pressure drop or cell voltage, too great a deterioration of electrodes, evidence of matrix degradation, or cross leaks were cause for rejection. Good cells were added to provide a total of five 15-cell modules. Originally the modules were equipped with magnesium end plates and 0.64 cm (1/4-in.) diameter tubing and fittings. During refurbishment, all module liquid tubing and fittings were increased to a 0.95 cm (3/8 in.) diameter configuration. This was done to minimize system pressure drop in order to obtain a higher flow in the individual cells for easier gas purging. New turnaround plates with less pressure drop were also added to the modules. Magnesium end plates were replaced with stainless steel units to eliminate a significant corrosion couple.

Refurbishment of the 2-phase liquid-gas separator was not accomplished due to the Advance Electrochemical Products Division of Allis-Chalmers going out of business. As a result it was necessary to redesign the system accommodating the high pressure drop characteristics of the old separator.

The fluid circuits were modified by increasing the size of the plumbing in the electrolyte circulation loop, and replacing existing valves and other components with more reliable units that would also cause less pressure drop. The electrolyte circulation pump was shifted to the downstream side of the separator. This helped minimize the amount of low-pressure plumbing in the system and reduced the change of pressure sensed by the H_2/H_2O differential pressure switch each time the circulating pump operated. Numerous additional pressure sensors and temperature sensors were incorporated to improve the operator's ability to predict and follow changes as they occurred and to determine their effect on system performance.

All new components added to the system were compatible with the KOH electrolyte. Past experience indicated that the KOH had a tendency to migrate to places that were ordinarily not designed to be compatible with the KOH electrolyte. A good example of this was the water accumulator, which was isolated from the KOH solution by a check valve, a solenoid valve, a manual valve, a regulator, and a 3-way solenoid valve, and yet the KOH did get into the accumulator and react with the bladder and aluminum housing. Originally, the differential pressure switches were not expected to come in contact with KOH. However, malfunctions in modules and liquid carryover caused considerable damage to the noncompatible parts of the differential pressure switches. General characteristics of the original system design was retained.

The major changes to the electronic circuits were replacement of those components that indicated poor performance during past testing as well as replacement of components determined unacceptable by design evaluation. The electrical packaging was rearranged and electrical integrity improved in areas of printed circuit card (PCC) installation and wire routing. Wiring was upgraded to aerospace standards.

Packaging was accomplished to improve reliability and general isolation of electrical circuits from the KOH fluid system. An automatic water relief system was added to eliminate the flooding of the gas cavity. Controls were added to allow wetting of the O_2 section of one module while leaving the remaining modules on the line. Drift and sensitivity of the current control potentiometer was corrected. Control signals were incorporated to interface with the automatic monitoring and safe control system. All module current control circuits were made independent, thus removing the single-point failures of relays and diodes which occurred during the 90-day Space Vehicle Simulator run. All coldplate electronics were redesigned to eliminate possible effects that water condensate might have on the system.

New instrumentation was added to the system to assist the operating engineers in diagnosing problems, evaluating performance, and predicting failures. Instrumentation existing on the original design was augmented by the following:

- Electrolyte pressure drop across modules and separator.
- N_2 pressures: supply and reservoir.
- H_2 accumulator pressure.
- Coolant supply temperature to coldplate and condenser.
- H_2 and O_2 temperatures into and leaving condenser.
- Water temperature leaving accumulator.
- Condensate temperature.
- Separator temperature.
- Circulating electrolyte temperature at various places in the circuit.

The overall purpose of these changes was to improve the reliability of the total system. Modules and cells were refurbished to regain operating capability. Refurbishing all fluid-flow hardware and electronic hardware was accomplished to obtain high reliability, more versatility, and data for long life performance. These changes were expected to eliminate failures due to faulty equipment and concentrate efforts on verifying cell and module design limits and capabilities. Approximately 100 data points were to be recorded by the automatic monitoring system each minute of unit operation. This comprehensive coverage of parameters provided a complete picture of changes that were taking place in cells, modules, fluid circuits, and electrical circuits. It would identify which parameter changes precede which failures. These 100 data points were to provide information for automatic monitoring for safe control as well as a measurement of the long life potential of initial components within the total water electrolysis system.

5.2 Module Acceptance Testing

Two separate acceptance tests were conducted on the SVFU modules. The first was immediately after refurbishment at the Allis-Chalmers facility. This period of performance was to be for 48-continuous hours. The second test was performed by Life Systems, Inc. approximately 6 months after the first test. Three of the modules did not receive any testing or operation between the two acceptance test periods. The other two modules which were initially defined as spare units were subjected to short term testing and one module was subjected to a 100-hour checkout test. Total duration of this short term system checkout testing was slightly greater than 600 hours.

5.2.1 Test Procedures and Facilities at Allis Chalmers

Prior to acceptance testing the original modules were disassembled, checked cell by cell and then reassembled with new cells wherever necessary. After reassembly the modules were subjected to flow tests, external leak tests, cross-leak tests, and then acceptance tests. A simplified schematic of the test setup used for acceptance testing is shown on Figure 5-1. Requirements of the test included that: all measurements be made with

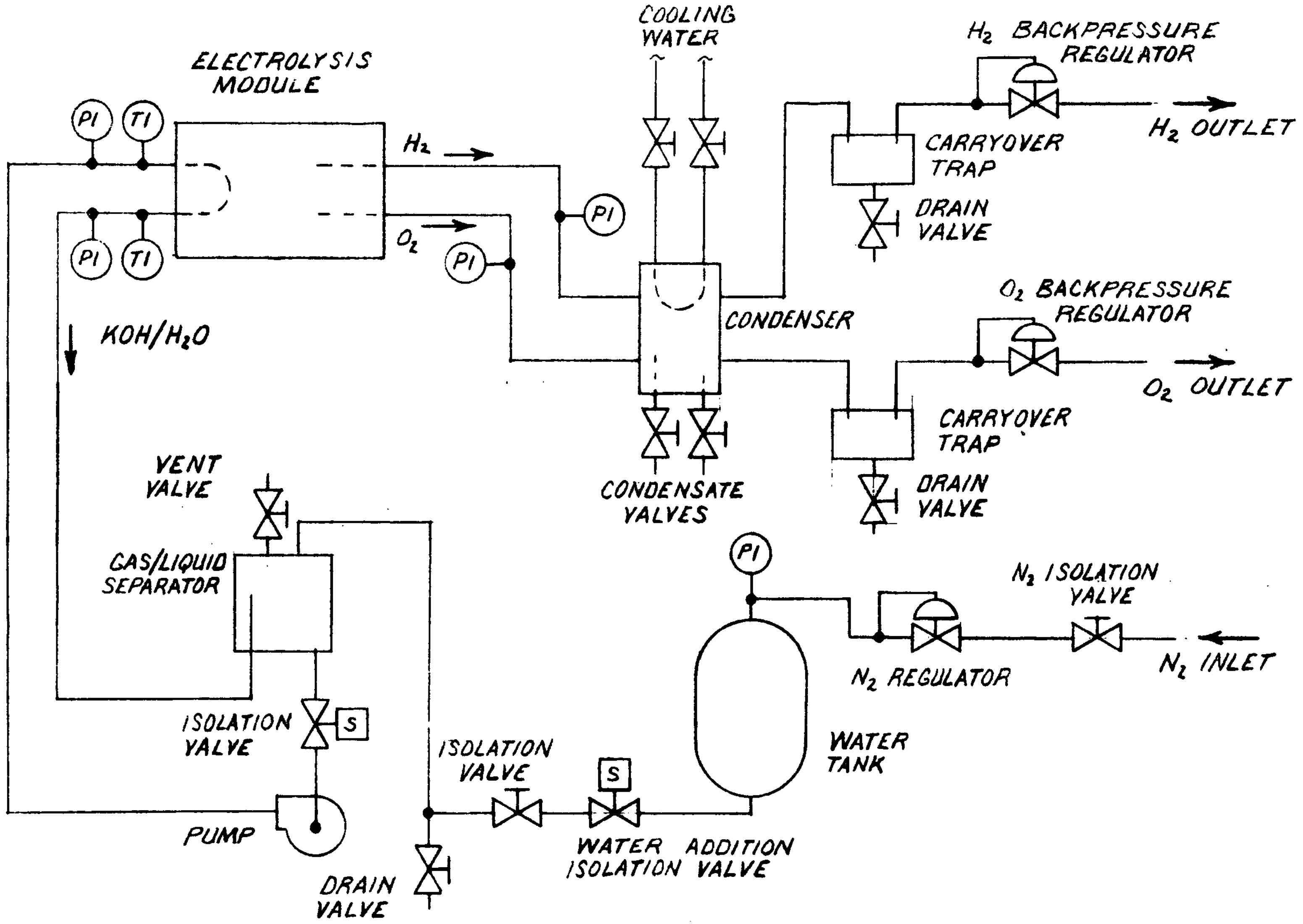


FIGURE 5-1
MECHANICAL SCHEMATIC OF
ALLIS-CHALMERS MODULE TEST SET-UP

calibrated instrumentation, bench instruments would measure amperage and pressure only, a digital voltmeter would measure voltages, feed water would be deionized and supplied from a reservoir pressurized 3.45×10^3 to 13.9×10^3 N/m^2 gage (0.5 to 2 psig) below the O_2 pressure, the amount of water consumed would be measured, and thermostat on and off points would be measured and recorded.

Test measurements to be made included: quantity of water electrolyzed, duration of test, currents and voltages to electrolysis stacks, pressure and temperature of feed water and product gases, coolant flow temperature at inlet and outlet and volume of output gases.

Operation of the acceptance test required heating the modules to operating temperature using the internal cell and end plate heaters. Coolant flow was established through the condenser at a rate sufficient to condense trapped liquid and at approximately 283°K (50°F). Voltage was applied to the module using the regulated dc power supply until approximately 5 amperes was being supplied to the module. Only one module was tested at a time. Circulation of electrolyte was continuous with the module temperature controlled between 350 and 353°K (170 and 175°F). After power application the oxygen-side pressure was increased with the back pressure regulator to about 6.89×10^4 N/m^2 gage (10 psig). Hydrogen back pressure regulator was then increased to maintain the hydrogen pressure 6.89×10^3 to 13.8×10^3 N/m^2 gage (1 to 2 psig) above the oxygen. The solenoid valve between the module and the water reservoir was opened and the reservoir pressure maintained 6.89×10^3 to 13.8×10^3 N/m^2 gage (1 to 2 psig) below the oxygen pressure. Current was applied at 5 amperes for 1 to 2 hours, then it was increased to 8 amperes for 10 to 20 hours, finally the current was increased to 12.0 amperes for the remainder of the 48-hour test period.

5.2.2 Acceptance Testing at Allis-Chalmers (A-C)

Actual testing and test monitoring performed at the A-C facilities was conducted under the sponsorship of the McDonnell Douglas Astronautics Company Independent Research and Development funding.

All modules performed well. Figures 5-2 through 5-6 show the data on the performance of the modules during the 48-hour acceptance test. The data has been compared with other data collected during acceptance testing at LSI and during steady state performance/endurance testing. Data for modules 2 through 5 deviate less than 2% for all test comparison points. Data for module 1 deviates about 4.5%. A review of the data sheets on this module indicates unusually low cell and module voltages that do not correlate with data collected anywhere else (including acceptance testing prior to the 90-day test). All the data indicates that the module voltage should be about 23.4 to 23.6 for the conditions of operation indicated. The only explanation that can be put forth at this time is either human error in reading the data or the instrumentation was not presenting true values. The unusual shape of the curve on Figure 5-4 for module 3 was caused by the temperature controller becoming disconnected. The module did not turn off. Recovery after reconnecting the controller indicated that damage had not been done. This test was performed over a weekend and when the engineer came in he found the unit shutdown after 50.5 hours. Voltage data was not available for the last 8 hours because of unattended operation. To insure that damage had not been done the unit was restarted on the next work day and operated 6 hours at 12 amperes. Data recorded was good and hence the acceptance test was considered complete for the module.

5.2.3 Test Procedures and Facilities at Life Systems, Inc.

Two test benches were available for module acceptance and characterization testing. Test bench #1 was used for acceptance testing of modules 2, 3, 4 and 1 in that order. Test bench #2 was used to perform acceptance testing and characterization testing on module 5 over a 150 to 300 hour test period. Both test benches were functionally identical.

5.2.3.1 Test Facilities

The test rigs were designed and fabricated to permit performance characterization and continuous long-term operation of H_2O electrolysis modules using a static feed mechanism with a circulating electrolyte loop. With these test rigs, the operator had the capability to control module current, H_2O pressure level, O_2 to H_2O pressure differential, and H_2 to H_2O pressure differential.

FIGURE 5-2

ACCEPTANCE TEST MODULE 1A

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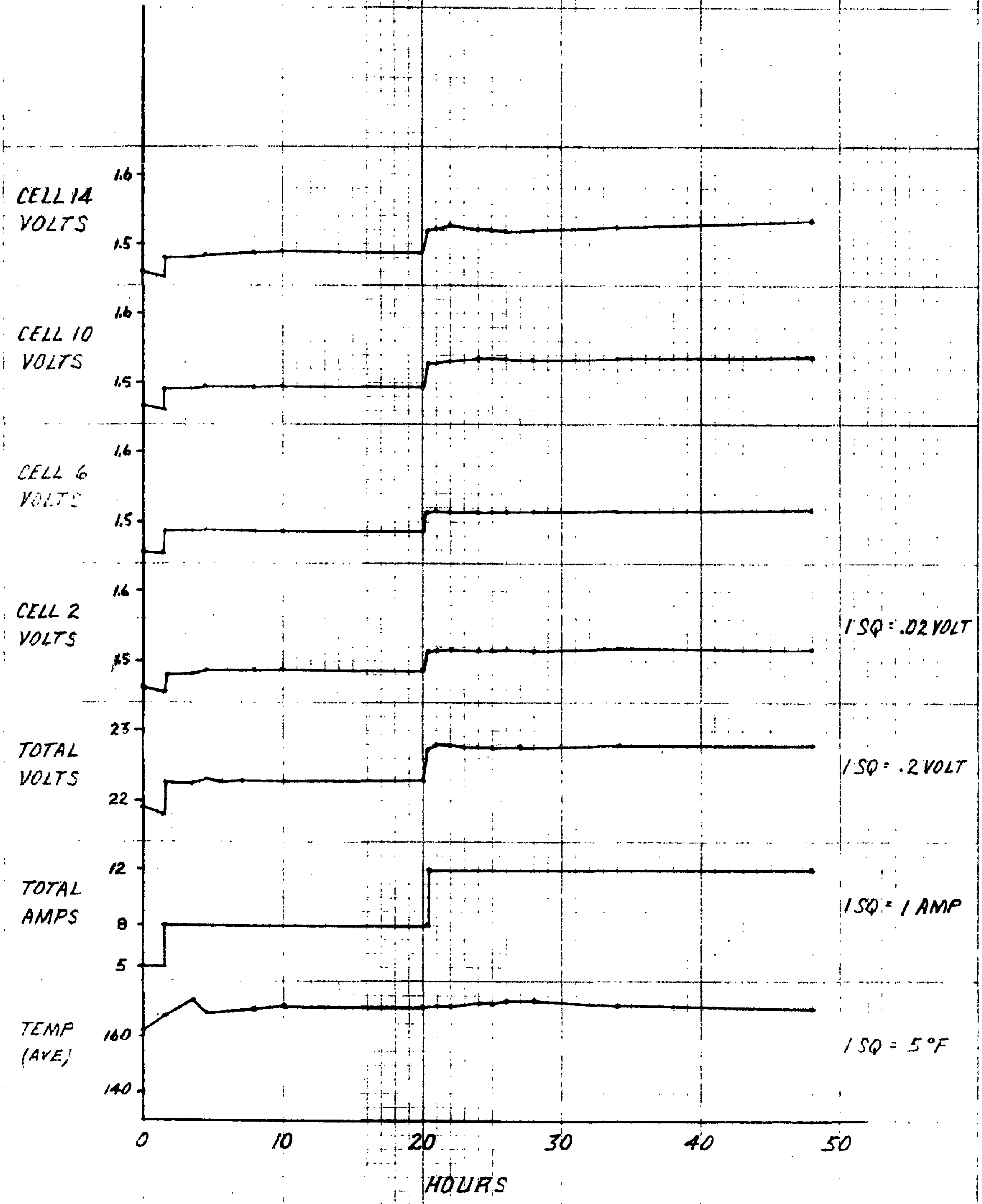

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FIGURE 5-3
ACCEPTANCE TEST MODULE 2A
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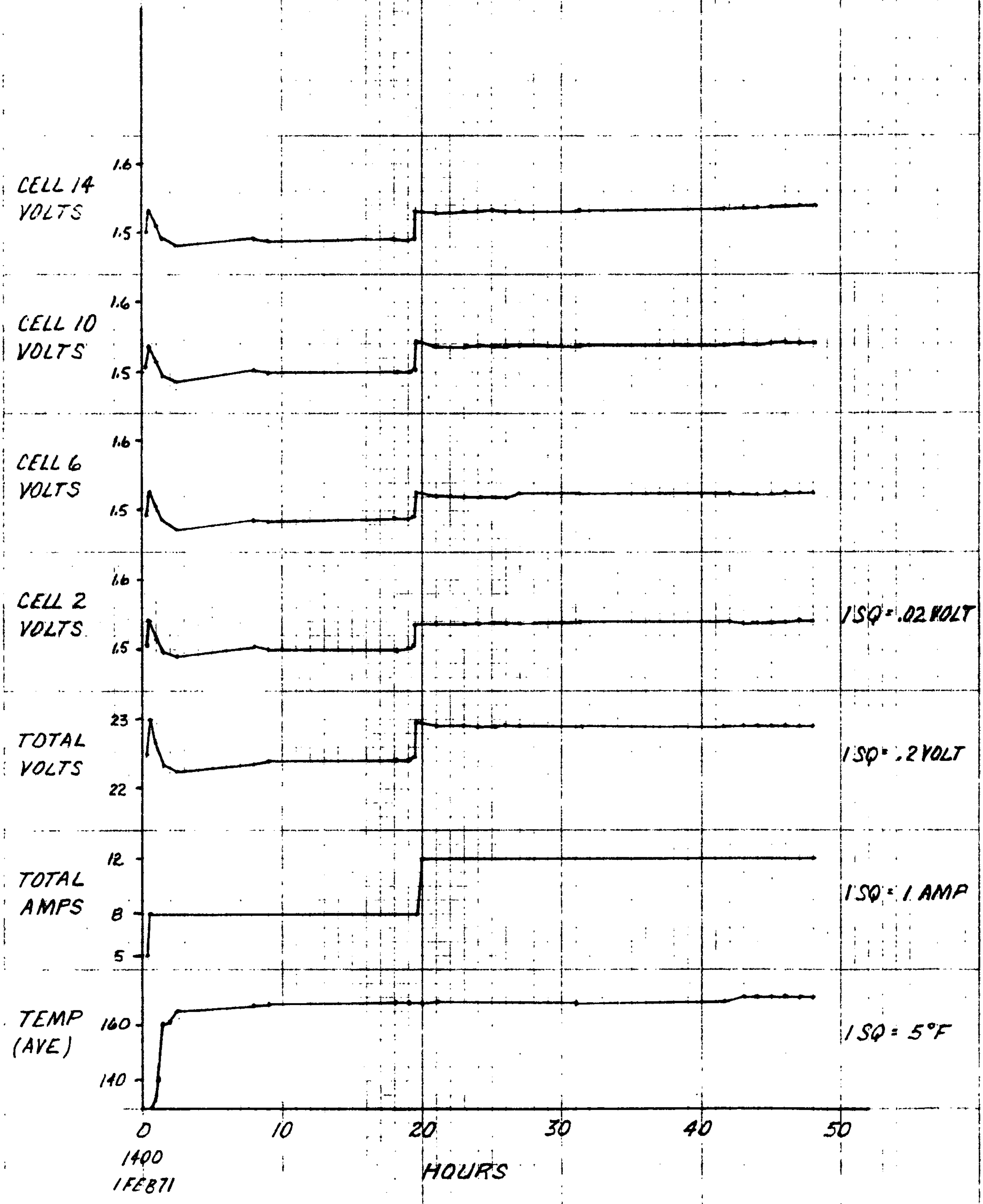

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FIGURE 5-4

ACCEPTANCE TEST MODULE 3A

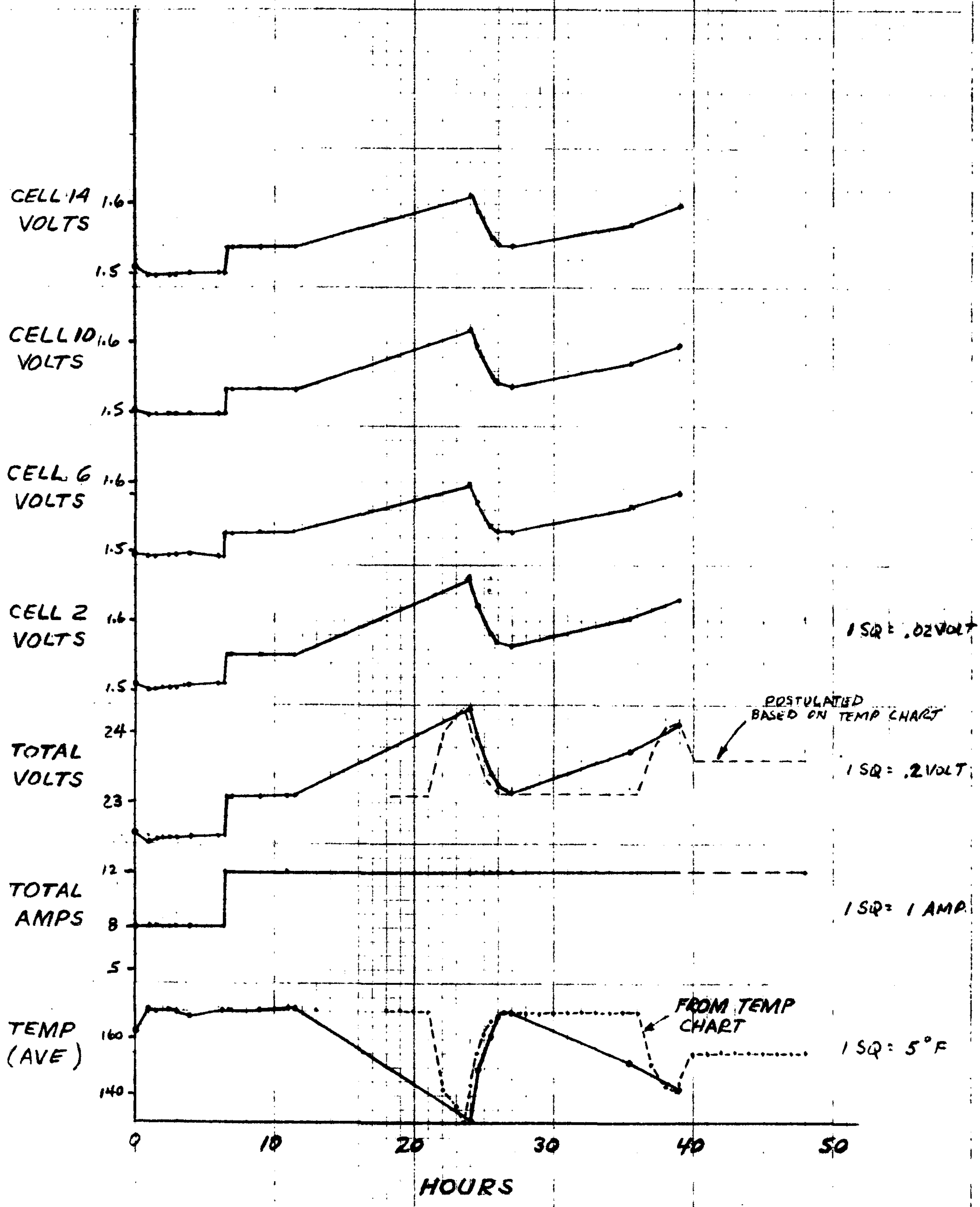

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FIGURE 5-5

ACCEPTANCE TEST MODULE 4A

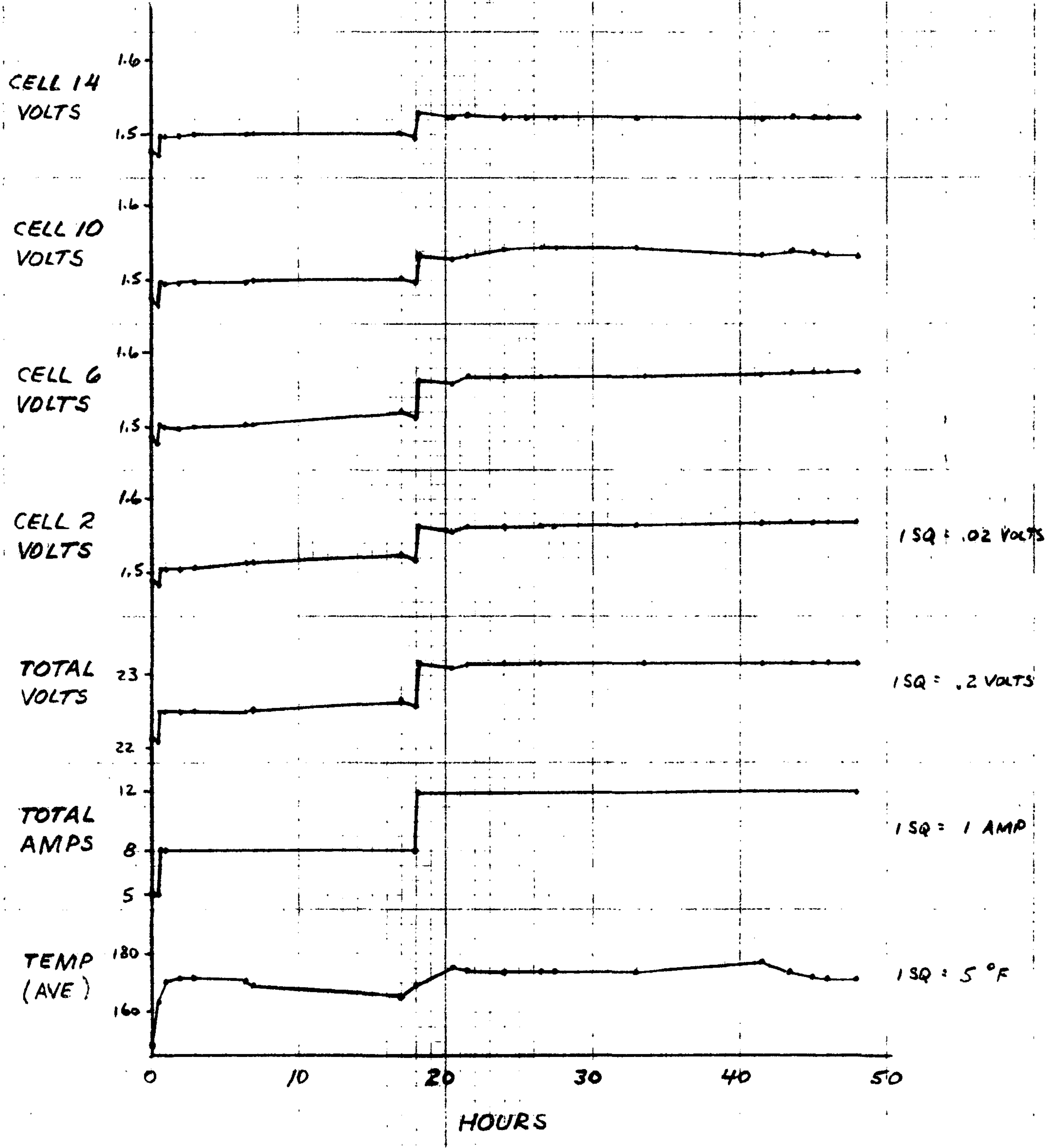

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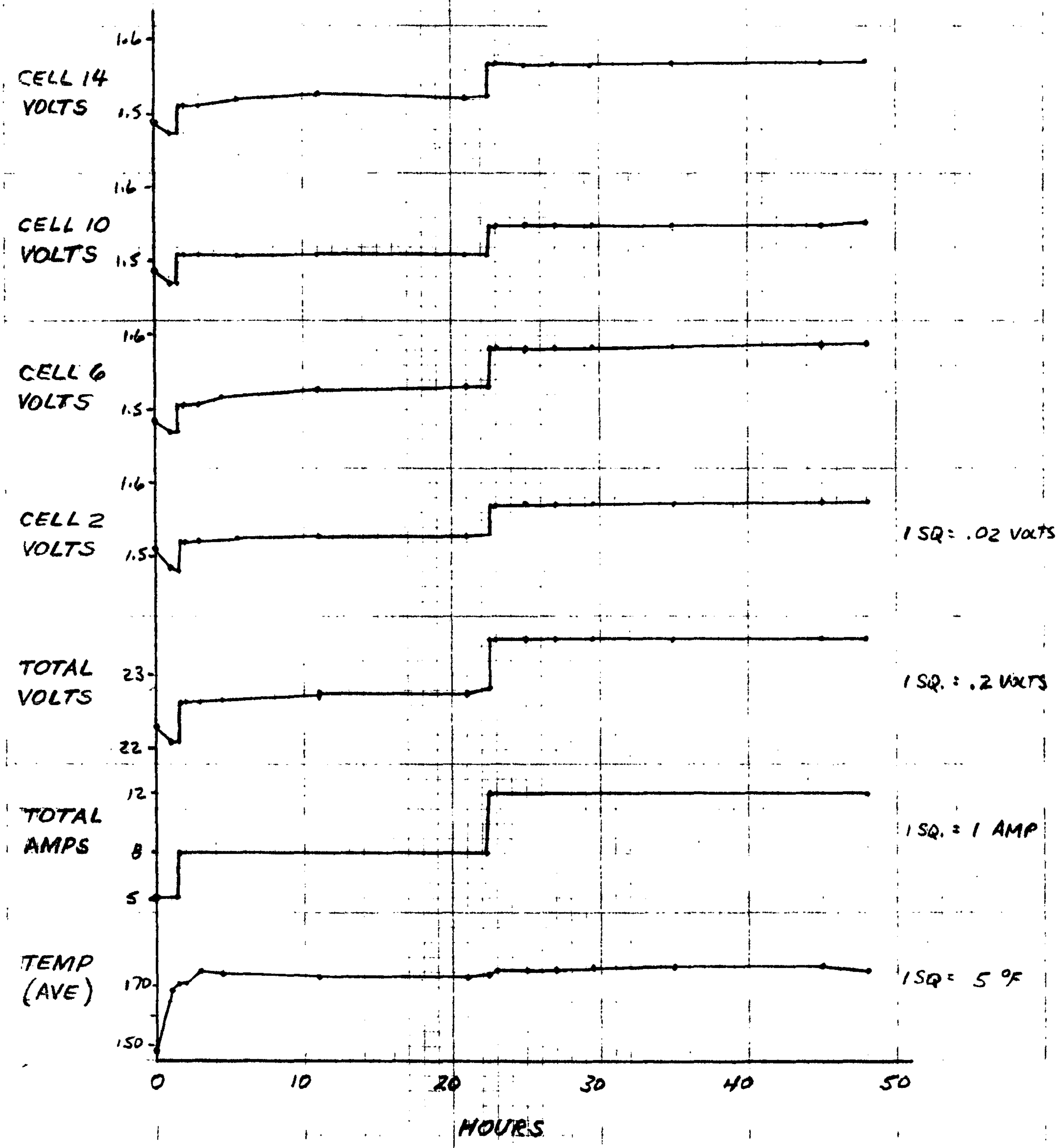
FIGURE 5-6

ACCEPTANCE TEST MODULE SA



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The operator could monitor the following dependent parameters: individual cell voltages, module voltage, and O_2 and H_2 flow rates. The amount of H_2O condensed could be determined by withdrawing condensate from traps located in both the O_2 and H_2 lines. Besides the above-mentioned instrumentation, the test rig was equipped with connectors to continuous type recorders available for recording of individual cell voltages, module voltage, module current, 4 module temperatures, and two test system temperatures.

The test benches were equipped with automatic shutdown type safety features to protect the modules from possible damage due to out-of-tolerance operation. The four conditions that would trigger an automatic shutdown and their set points are:

a. H_2O pressures greater than 20.6×10^4 N/m^2 gage (30 psig)
b. H_2 to H_2O pressure differentials greater than 2.76×10^4 N/m^2 differential (4 psid) and less than 6.89×10^3 N/m^2 differential (1 psid)
c. Temperature greater than 367°K (200°F) and
d. Any individual cell voltage greater than 1.7 volts.

All shutdown set points were adjustable. The overtemperature and cell voltage limits were adjustable by moving the trip points of the limit switch mounted on the strip chart recorder.

Figure 5-7 is a functional plumbing schematic applicable for both test benches #1 and #2. The test benches provided for product gas pressure and flow monitoring and control, feeding H_2O to the module, dehumidification of product gases, and electrolyte recirculation to enable cavity degassing. With these test benches, the operator was capable of maintaining a constant pressure, constant pressure differentials, and constant gas production rates. The pressure levels were controlled by three pressure regulators. The current was controlled by a constant current power supply. Circulating loop temperature was maintained by heater wire wrapped around circulating loop tubing. A 28 volt DC power supply was used to supply power to cell and endplate heaters.

Discussion of the test bench operation is facilitated by referring to Figure 5-7. Oxygen and H_2 are generated in the module, each gas passed through quick

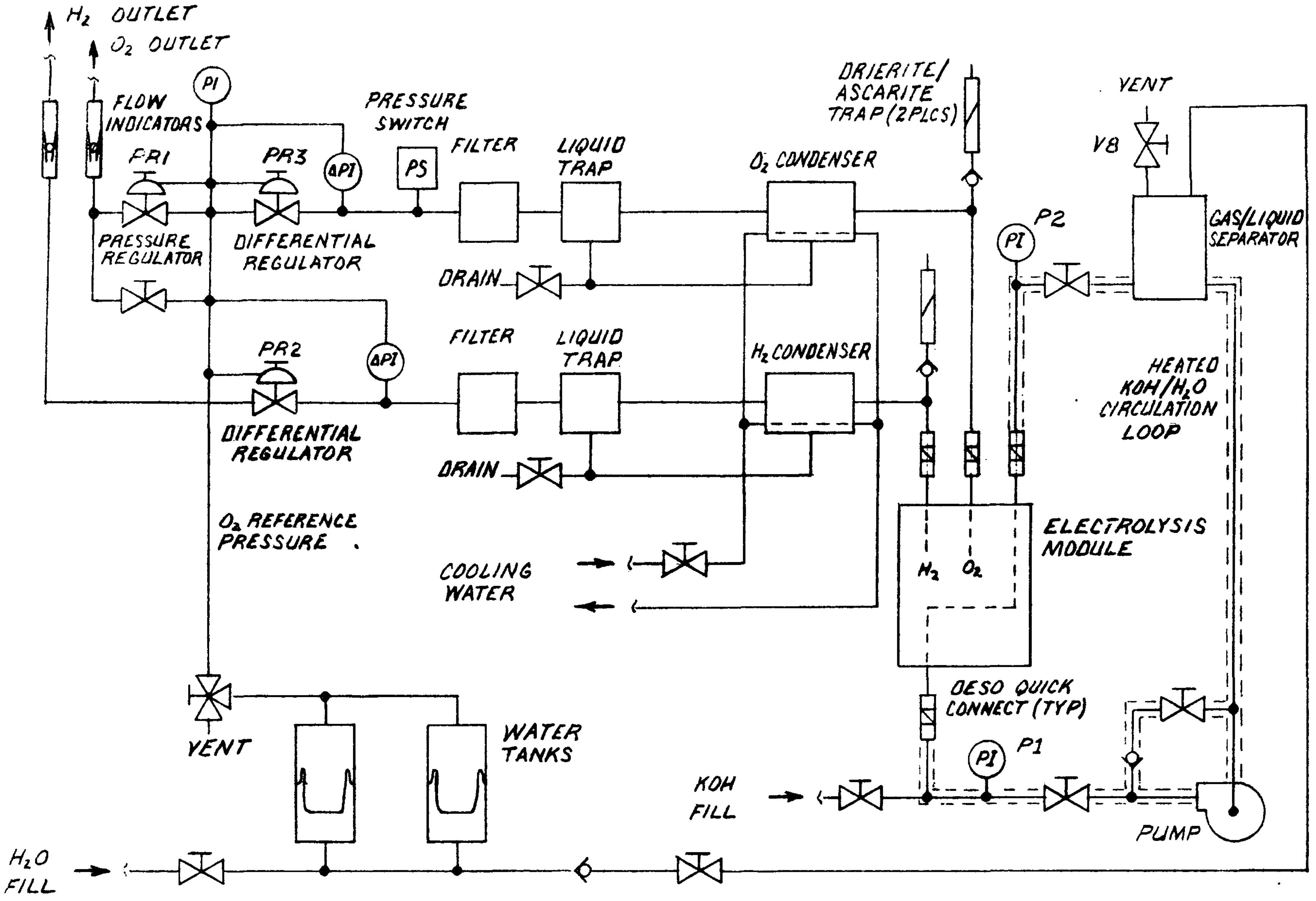


FIGURE 5-7
MECHANICAL SCHEMATIC OF
LIFE SYSTEMS, INC. MODULE TEST SET-UP

connects, and then flowed through a water-cooled condenser network, a trap to collect the condensate, and a filter to remove any entrained moisture from the gases.

Pressure and flow control will be described starting from the O_2 and H_2 vent lines. Prior to these vents the gases passed through individual rotameters to continuously indicate flow rates of the gases. Pressure regulator, PR1, located in the O_2 line was used to adjust the total system pressure level. The pressure level upstream of PR1 was also used to reference the H_2O feed tanks. Pressure regulator PR3 adjusted the O_2 pressure to the desired value above the H_2O pressure, while PR2 adjusted the H_2 pressure to the desired value above the H_2O pressure.

The H_2O feed loop consisted of one large reservoir tank in Bench #2 and of two smaller tanks in Bench #1. Each tank was divided into a gas and a liquid compartment by a flexible diaphragm. Oxygen pressure, upstream of PR1, was used to pressure reference the feed water to the product gas pressures. The liquid sides of the bladder tanks were connected through shutoff valves and check valves to the liquid-gas separators in the electrolyte circulating loop. Water was automatically drawn from the tanks into the circulating loop to replace that water electrolyzed and that lost as product gas humidity.

The electrolyte circulation loop consisted of a pump, a pump bypass loop, module inlet and outlet liquid pressure gages, and a liquid-gas separator. The pump was operated continuously. A bypass loop containing a 6.89×10^3 N/m^2 gage (1 psig) check valve and flow control valve adjusted the total flow through the module. Module inlet and outlet pressure were monitored on gages P1 and P2. Gases accumulated in the liquid-gas separator were vented via V8.

Check valves with a cracking pressure of 2.26×10^3 N/m^2 gage (0.33 psig) and tubes filled with Ascarite and Drierite were connected to both product gas lines. These check valves and adsorbent tubes came into function after an automatic or manual shutdown. After shutdown, chemical recombination of the product gases typically tends to create a vacuum within the system, thus creating the possibility for H_2O to be sucked into the gas cavities from the feed tanks. As the vacuum level within the module reached 2.26×10^3 N/m^2 (1/3 psi) below atmospheric pressure, the check valves opened and allowed air to enter the O_2 and H_2 cavities. This air was stripped of moisture and CO_2 by the Drierite and Ascarite in the tubes. The 2.26×10^3 N/m^2 (1/3 psi) was equivalent to the difference in height between module and H_2O feed tanks, thus preventing module flooding.

The electrical controls of the test stand consisted of a power ON/OFF switch with indicator lights, a constant current regulated DC power supply with upper voltage level control and constant current control used to adjust module current levels, and a cell and endplate heater power supply actuated through an ON/OFF switch with an indicator light, a DC voltmeter, and a DC ammeter. The total system time was recorded on a resettable elapsed time meter. A light indicated when module power was applied and when the timer was in operation. A pyrometer was used to read module temperatures by using a thermocouple selector switch from positions 1 through 4. The 15 individual cell voltages were read on a voltmeter (0 to 3 volt scale) using a selector switch. A 16th position was used to read total module voltage (0 to 30 volt scale).

The automatic shutdown provisions could be overriden by switches located on the front control panel. If a malfunction occurred, a red light identified the particular malfunction. An amber light indicated if the shutdown parameter was overriden. If a malfunction occurred during an override condition, both amber and red lights were lighted.

5.2.3.2 Test Procedures

(a) 100-Hour Module Acceptance Tests

This test consisted of testing 4 modules for a period of 100 hours each on Test Bench #1 and one module for 150 to 300 hours on Test Bench #2. The modules were tested at the nominal operating conditions given in Table 5-1.

Maximum operating limits shown in Table 5-2 were never exceeded during all acceptance testing. The data collected for each module during its acceptance test is shown with its collection frequency in Table 5-3.

The O_2 and H_2 gases were bubbled through graduated cylinder H_2O bubblers, containing 1000 cc of distilled water. The pH of the distilled water was determined at test termination to detect if any KOH aerosol was contained in the effluent gases as obtained from the front panel vent bulkheads. The pH of the water was measured using a Corning Model M109 Digital pH meter.

The quantity of KOH collected within the condensate in the respective traps in the O_2 and H_2 lines was determined after completion of each 100-hour test using standard titration techniques.

(b) Module Characterization Test

A module was scheduled to undergo a characterization test using Test Bench #2. The operational limits as outlined above applied since the acceptance test was integral with the characterization tests. The test bench procedures cited previously also applied to the module characterization tests. The total acceptance and characterization test time ranged from 150 to 300 hours. During this time, 7 specific parametric tests, noted below, were performed. Between the parametric tests, the module was set to operate at nominal design conditions as cited under module acceptance testing above.

The following is a brief description of the module characterization tests. Data recording requirements for all tests were as outlined in Table 5-3.

(1) Initial Pressure Drop Test - The test was to establish the initial flow rate of a 35% solution of KOH through the water cavity of a module. This test would be repeated at the end of the testing to determine if any changes took place. Data was obtained for 3 flow rates with 2 sets of readings at each flow rate. The flow rates covered the range of 100 to 800 cc/minute.

TABLE 5-1

NOMINAL OPERATING CONDITIONS

Current	11.3 amps
Temperature	344 - 355°K (160 - 180°F)
H_2O Pressure	18.6×10^4 N/m^2 gage (27 psig)
H_2 to H_2O Pressure Differential	$6.89 \times 10^3 - 13.9 \times 10^3$ N/m^2 differential (1.0 - 2.0 psid) $H_2 > H_2O$
O_2 to H_2O Pressure Differential	$3.45 \times 10^3 - 6.89 \times 10^3$ N/m^2 differential (0.5 - 1.0 psid) $O_2 > H_2O$
Electrolyte	35% KOH w/w
Electrolyte Flush Rate	> 300 < 450 cc/min
Electrolyte Flush Frequency	Continuous

TABLE 5-2

OPERATIONAL LIMITS

Temperature	322 - 366°K (120 - 200°F)
Pressure	$0 - 20.6 \times 10^4$ N/m^2 gage (0-30 psig)
Current	0-15 amps
Cell Voltage	0 - 1.7 volts
H_2 to O_2 Pressure Differential	$3.45 \times 10^3 - 13.9 \times 10^3$ N/m^2 differential (0.5 - 2.0 psid)
O_2 to H_2O Pressure Differential	$3.45 \times 10^3 - 13.9 \times 10^3$ N/m^2 differential (0.5 - 2.0 psid)
H_2 to H_2O Pressure Differential	$6.89 \times 10^3 - 2.76 \times 10^4$ N/m^2 differential (1.0 - 4.0 psid)

Table 5-3

ACCEPTANCE AND CHARACTERIZATION TEST DATA REQUIREMENTS

No. of Parameters	Parameter	Units	Frequency[(a)] A	B	C
1	Date	Month/Day	X	X	X
1	Clock Time	Hours	X	X	X
1	Operating Time	Hours	X	X	X
15	Cell Voltage	Volts	X	X	
1	Module Voltage	Volts	X	X	
1	Module Current	Amp	X	X	
4	Module Temperature	°F	X	X	
1	KOH Inlet Temperature	°F	X	X	
1	Condenser H_2O Out Temperature	°F	X	X	
1	Ambient Temperature	°F	X	X	
1	H_2O Pressure	PSIG	X		
1	O_2 to H_2O Δ P	PSID	X		
1	H_2 to H_2O Δ P	PSID	X		
2	Circulating Loop Pressure	PSIG	X		
1	O_2 Flow Rate	CC/MIN	X		
1	H_2 Flow Rate	CC/MIN	X		
1	Barometric Pressure	MM HG	X		
1	pH in O_2	pH			X
1	pH in H_2	pH			X
1	KOH in O_2 Condensate	%			X(b)
1	KOH in H_2 Condensate	%			X(b)

(a) A = Every two hours during normal working day.
B = Continuous through chart recorders.
C = At scheduled test termination.

(b) Both at 100 hours and at scheduled test termination for characterization test of module 5.

(2) Effect of Current on Voltages for Various Parameters - This test was subdivided into 4 smaller tests: (a) Voltage Versus Current, (b) Vary O_2 Pressure, (c) Vary Module Temperature and (d) Vary Cavity Vent Rate. Cell and module voltages were recorded for current levels of 3, 6, 9, 12 and 15 amperes. Each current level was maintained until the voltage stabilized or for a maximum of 30 minutes. The system was returned to nominal operating conditions after completion of testing to prepare for test (b). The system operating pressure was reduced from 18.6×10^4 N/m^2 gage (27 psig) to 11.8×10^4 N/m^2 gage (15 psig) for this second test. Current levels of 3, 6, 9, 12 and 15 amperes were repeated and data recorded. After this test the system was again returned to nominal conditions. Test (c) required operation at 328°K (130°F). This was accomplished by lowering heater setting on the variac and/or turning off end plate and cell heaters. This new temperature was maintained for 2 hours. Data was recorded for current levels of 3, 6, 9, 12 and 15 amperes. Again the module was returned to nominal conditions after completing the test. Test (d) operated the module without continuous circulation of electrolyte. Initially, the module was operated with circulation for about 2 minutes to remove trapped gases, then the pump was stopped. Data was recorded. After 6 hours of operation or when any cell voltages reached 1.7 volts, the pump would be started and gas flushed from the module. Flushing was for 2 minutes only. If the system did not reach 1.7 volts, the system was to be operated for an additional 24 hours without circulation of electrolyte.

(3) KOH Aerosol Determination - Condensate collected from each product gas line was to be analyzed for KOH concentration. Measurements were to be to the nearest 0.1% by standard titration methods.

(4) H_2O mass balance - A mass balance based on total data collected, was to be performed at test termination. This balance was to take into account (through estimation) current versus time variations, parametric pressure fluctuations, and ambient and condenser temperatures.

(5) Pressure Drop Due to Recombination of Product Gases - At the scheduled termination of the characterization tests the separator was to be vented and then the module turned off; that is, current to zero, close H_2O feed valve, close pressure regulator and plug vent lines. Pressure readings were to be recorded to determine the time interval until H_2O pressure reaches zero psig or until the allowable pressure differential limits were reached.

(6) Final Pressure Drop Test - This was a repeat of the initial pressure drop test to determine if a degradation took place as a result of previous testing.

(7) Post-Characterization Torque Check - This was to determine if operation at temperature would have any affect on torque of tensioning bolts in the module.

(8) Adverse Orientation Test - After completing all other characterization and acceptance tests, Module #5 was to be tested in an adverse orientation. The module was to be mounted with the water cavity of each cell facing upward; that is, with all tube fittings pointing upward. The module was to be brought to nominal conditions of temperature, 18.6×10^4 N/m^2 gage (27 psig) pressure, 11.3 amperes current and continuous electrolyte circulation. Cell voltages and module temperatures were to be monitored by recorder. All other data was to be recorded at 2-hour intervals. The module was to be operated in this manner for 25 hours or until cell voltage reached 1.7 volts. If an out-of-tolerance condition was reached, the current level was to be reduced to 5.7 amperes (50% of 11.3 amps) and testing continued for 25 hours at the new current level or until an out-of-tolerance condition was reached (whichever came first). The module was then to be placed in a normal orientation and stable operation obtained for 2 hours and data recorded. Next, the module was placed with the water cavity of each cell facing downward; that is, with all tube fittings pointing downward. The module was to be brought to nominal condition as described above. The module would be

operated in this manner for 25 hours or until a cell voltage reached 1.7 volts. If an out-of-tolerance condition was reached, the current level was to be reduced to 5.7 amperes and testing continued until 25 hours was reached at the new current level or until an out-of-tolerance condition was reached (whichever came first). The module was then to be placed in a normal orientation and stable operation obtained for 2 hours and data recorded.

5.2.4 Acceptance Testing at Life Systems, Inc. (LSI)

The acceptance testing at LSI consisted of 100-hours of continuous operation at the nominal design conditions projected for the subsequent 26-week performance/endurance test at MDAC.

During the acceptance testing no individual cell of any module exceeded the prescribed upper limit of 1.7 volts. All other operating parameters were also held within the prescribed limits.

Figures 5-8 through 5-12 show some of the data collected during the acceptance testing of Modules #1 through #5. The parameters plotted versus operating time are: four cell voltages (#2, #6, #10, and #14), module voltage, module current and two of four module temperatures (#1 and #2). As can be seen, maximum module voltage never exceeded 23.9 volts per module which is equivalent to 1.59 volts per cell, average. The highest module voltage over the 100 hours of operation was Module #1, Figure 5-8. Its voltage, however, remained constant at 23.9 volts for the second 50 hours of acceptance testing. The best performer was Module #2. Its voltage remained between 23.0 and 23.5 volts throughout the 100 hours of testing. The range of module voltages for all five modules was 23.0 to 23.9 volts resulting in average cell voltages of 1.53 to 1.59 volts, respectively.

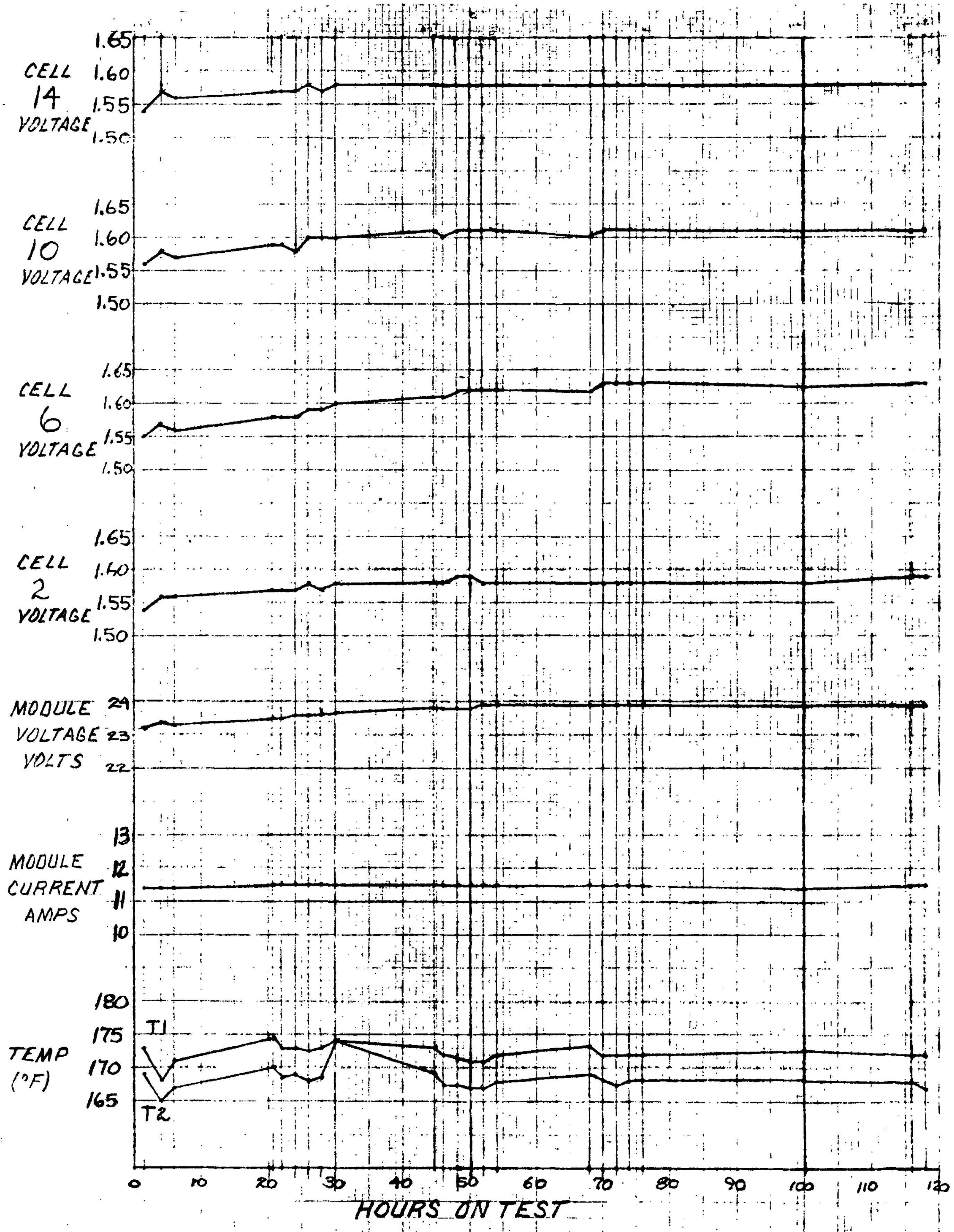


FIGURE 5-8 MODULE #1 ACCEPTANCE TEST DATA

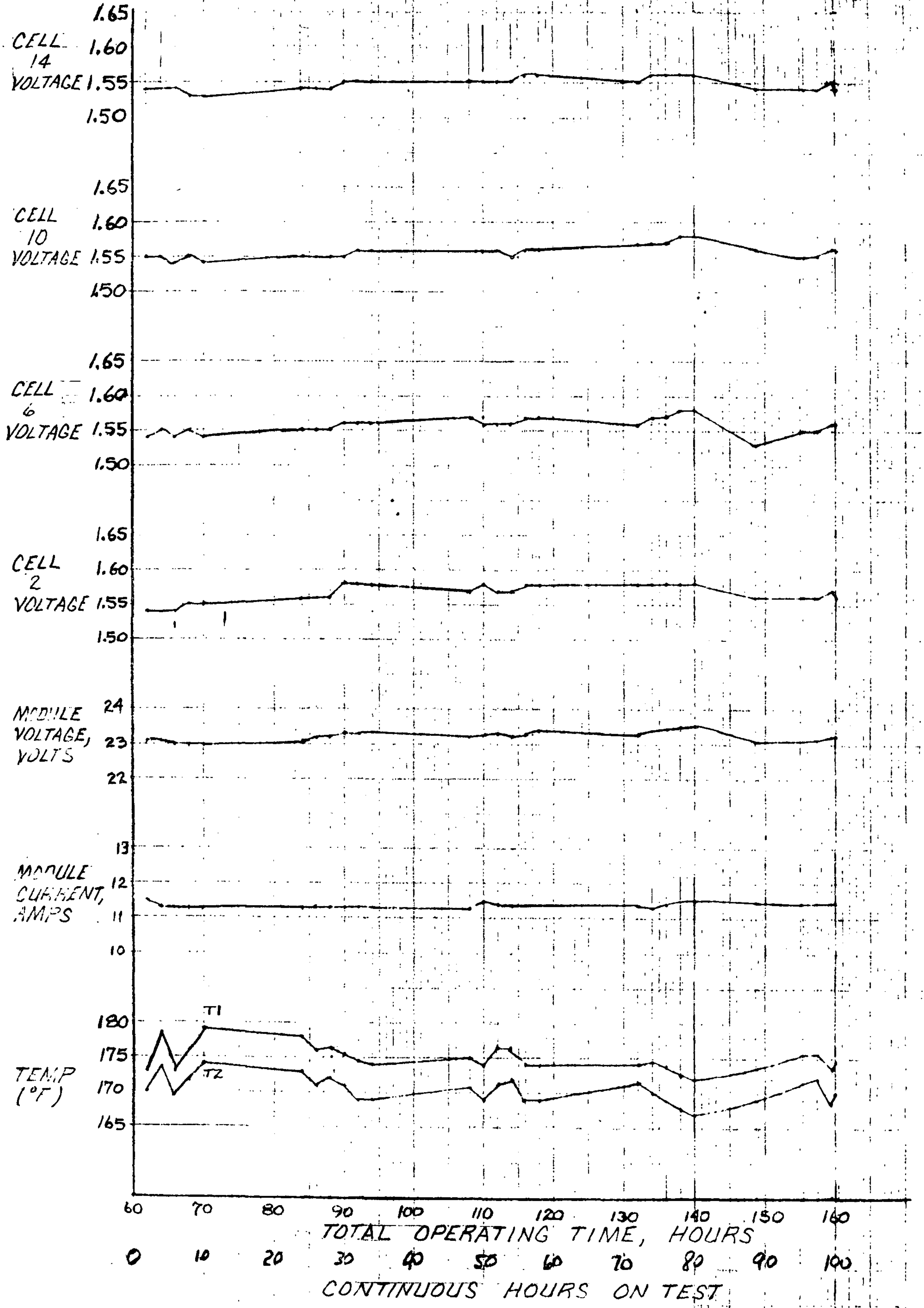


FIGURE 5-9 MODULE #2 ACCEPTANCE TEST DATA

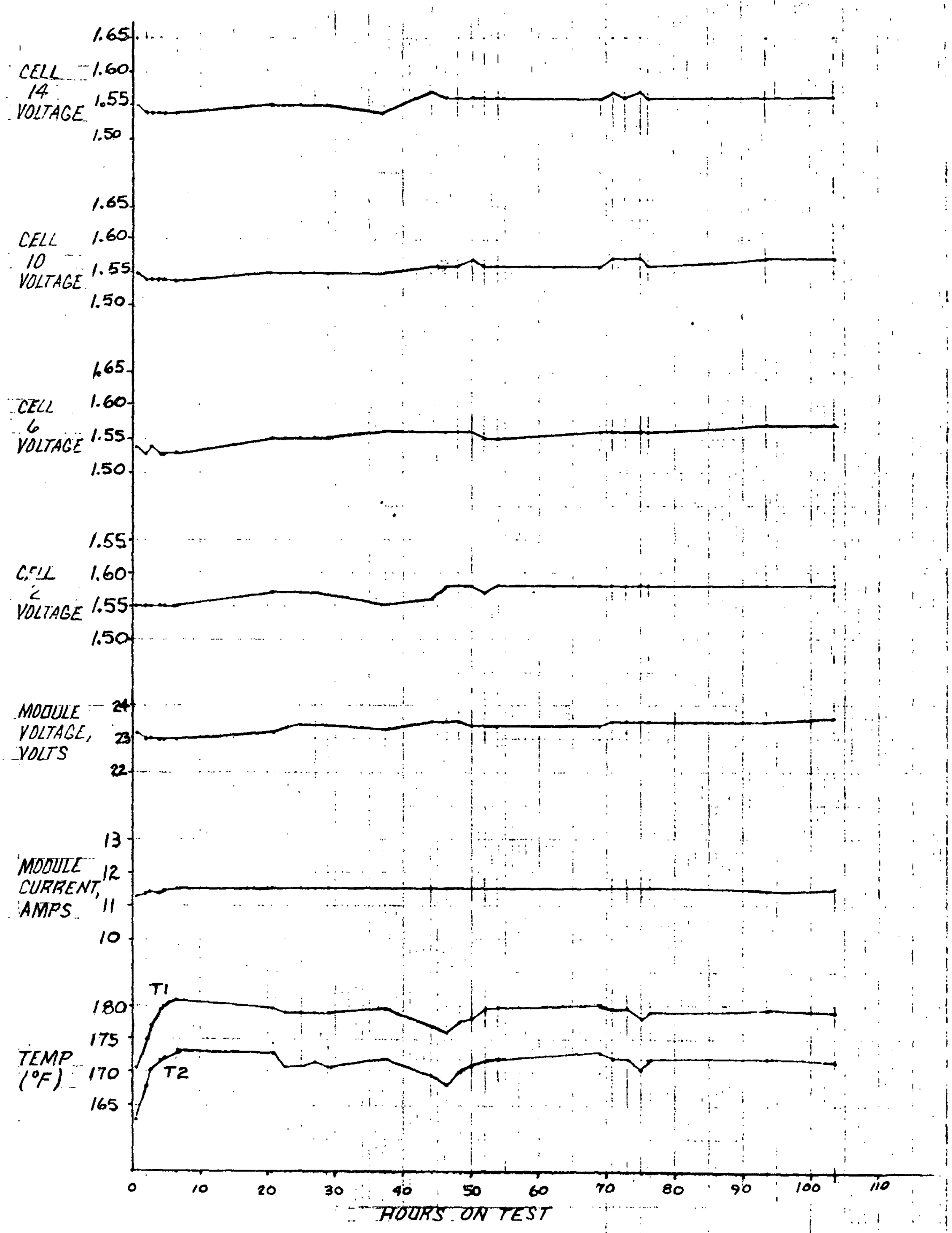


FIGURE 5-10 MODULE #3 ACCEPTANCE TEST DATA

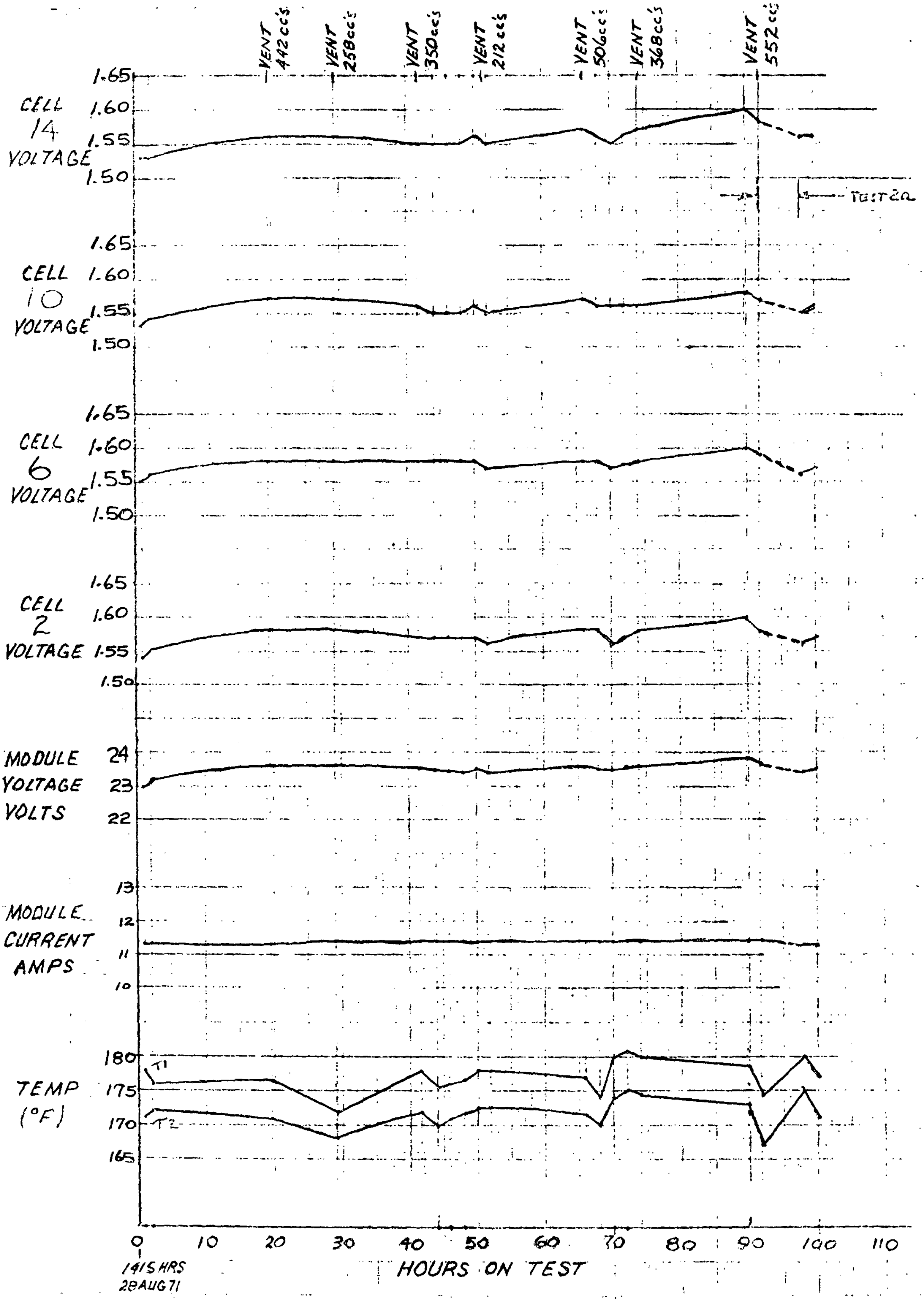


FIGURE 5-11. MODULE #4 ACCEPTANCE TEST DATA

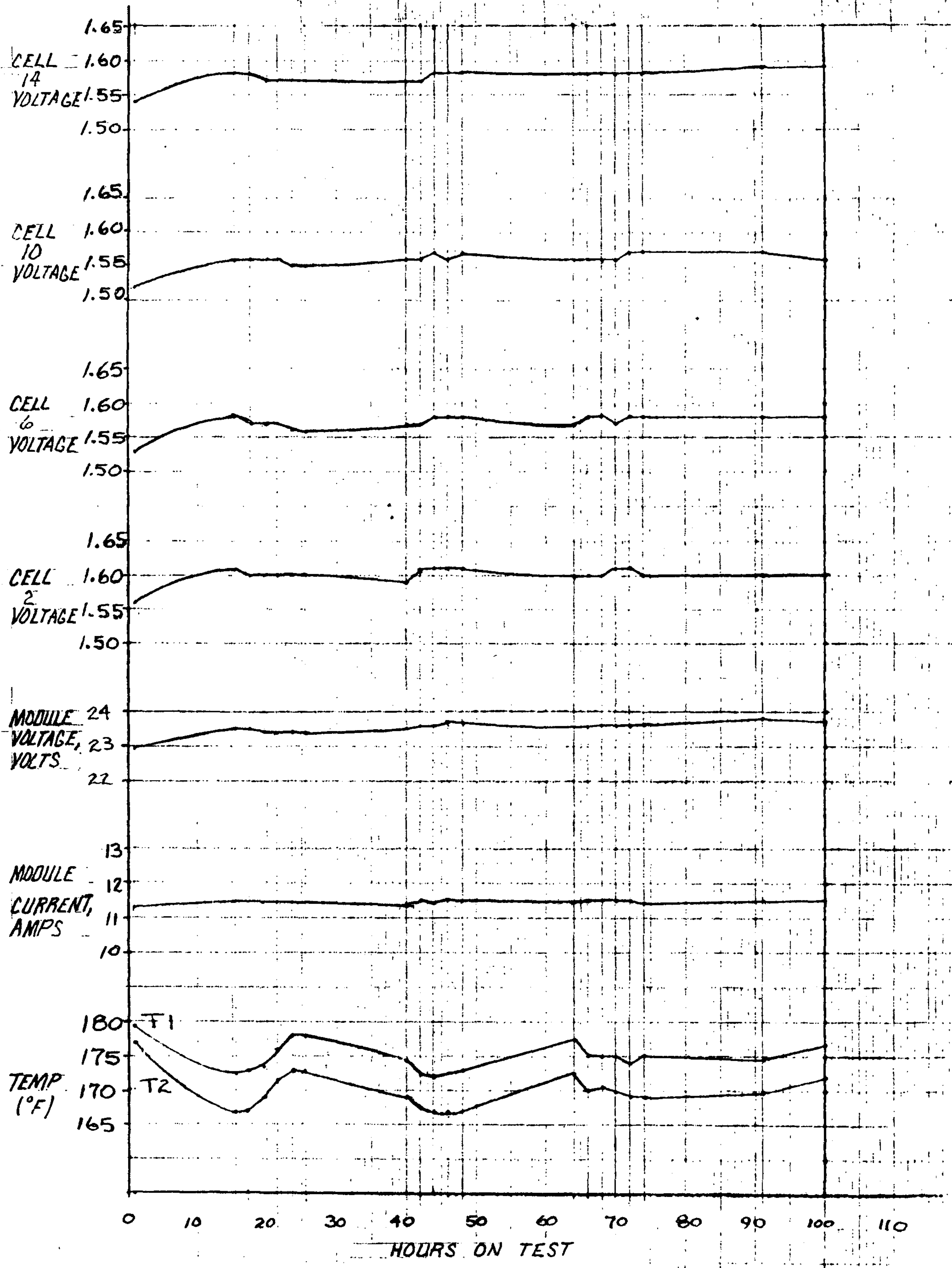


FIGURE 5-12 MODULE #5 ACCEPTANCE TEST DATA

Based on the results obtained during the 100 hours of acceptance testing of the five modules, LSI recommended all five modules acceptable for the 26-week competitive test to be conducted at MDAC. Module #4 developed a leak near Cell #15 during its post-acceptance characterization testing which LSI recommended be investigated and repaired prior to its installation into the system. LSI further recommended that Modules #1, #2, and #3 (1968 design version) be utilized as the primary modules for the testing with Modules #4 and #5 (1970 design version) delegated as the standby modules. This recommendation was based on the fact that during the acceptance testing no gassing due to stray electrolysis was observed in Modules #1, #2, and #3 while gassing rates were observed in varying amounts in Modules #4 and #5. These recommendations were discussed at the first test readiness meeting and the decision was made to use modules 2, 3 and 5. This was based on the fact that Module 1 appeared to have a crossleak and Module 4, as indicated by LSI, had excessive stray electrolysis. Both modules were to be repaired as soon as practicable.

5.2.5 Characterization Tests at Life Systems, Inc.

These tests were performed on Modules 4 and 5. Figure 5-13 shows the variation in four cell voltages, module voltage, module current and two module temperatures as a function of the 150 hours of acceptance and characterization testing on module #4. This module characterization testing consisted of obtaining cell voltages as a function of current density at three different operating conditions. The characterization tests were termed 2a, 2b, 2c (see paragraph 5.2.3.) and are indicated on Figure 5-13. Figures 5-14, 5-15, and 5-16 show the module voltage and the average cell voltage as a function of current and current density for tests 2a, 2b, and 2c, respectively.

Characterization tests on module 5 included: liquid cavity pressure drop tests, 120-hour adverse orientation test, and 80-hour static-feed-mode test. Figure 5-17 shows four cell voltages, module voltage, module current and two module temperatures as a function of time for the adverse orientation test. Figure 5-18 shows all 15 cell voltages, module voltage, module current and two module temperatures as a function of time for the 80 hours

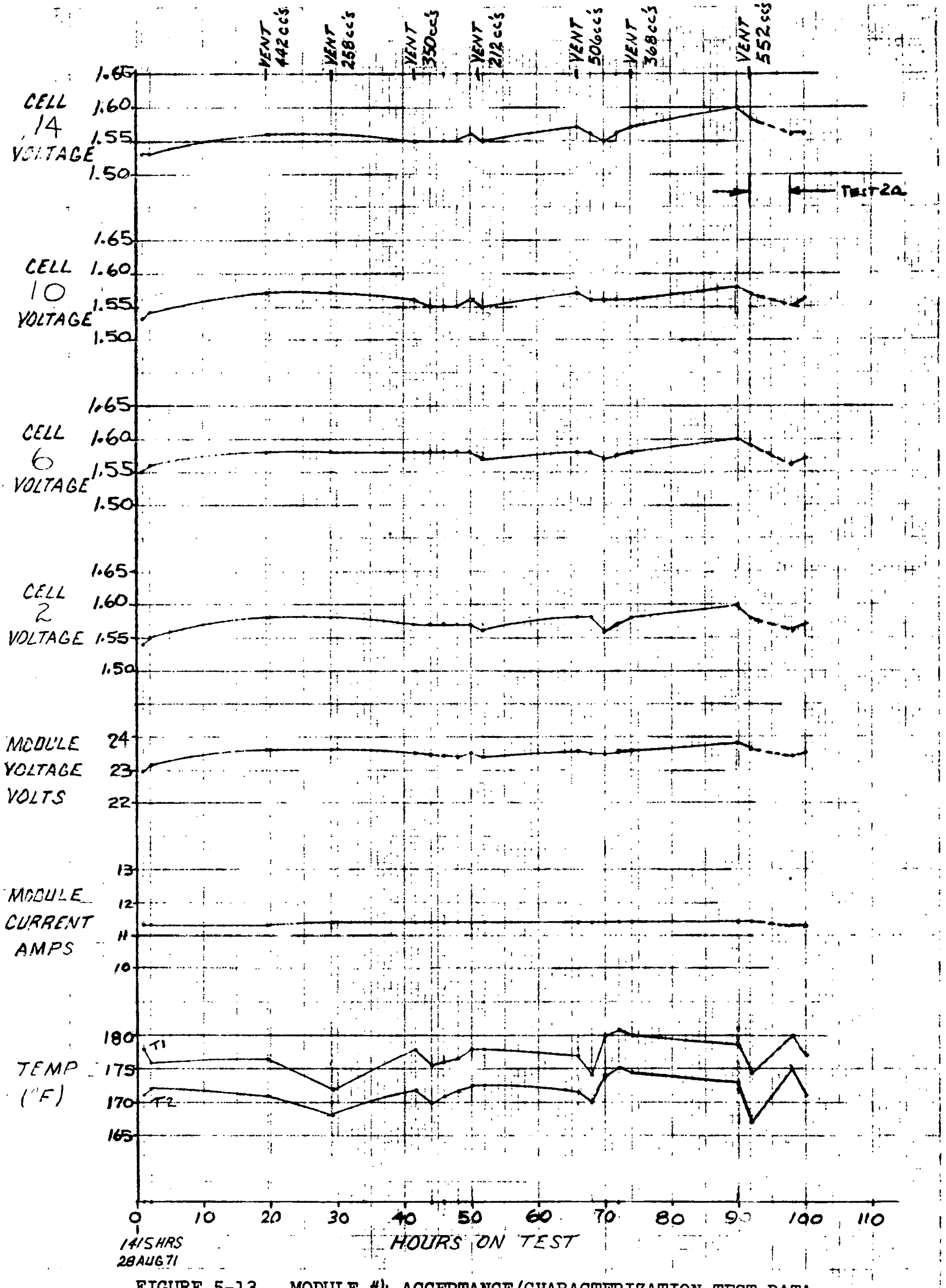


FIGURE 5-13. MODULE #4 ACCEPTANCE/CHARACTERIZATION TEST DATA

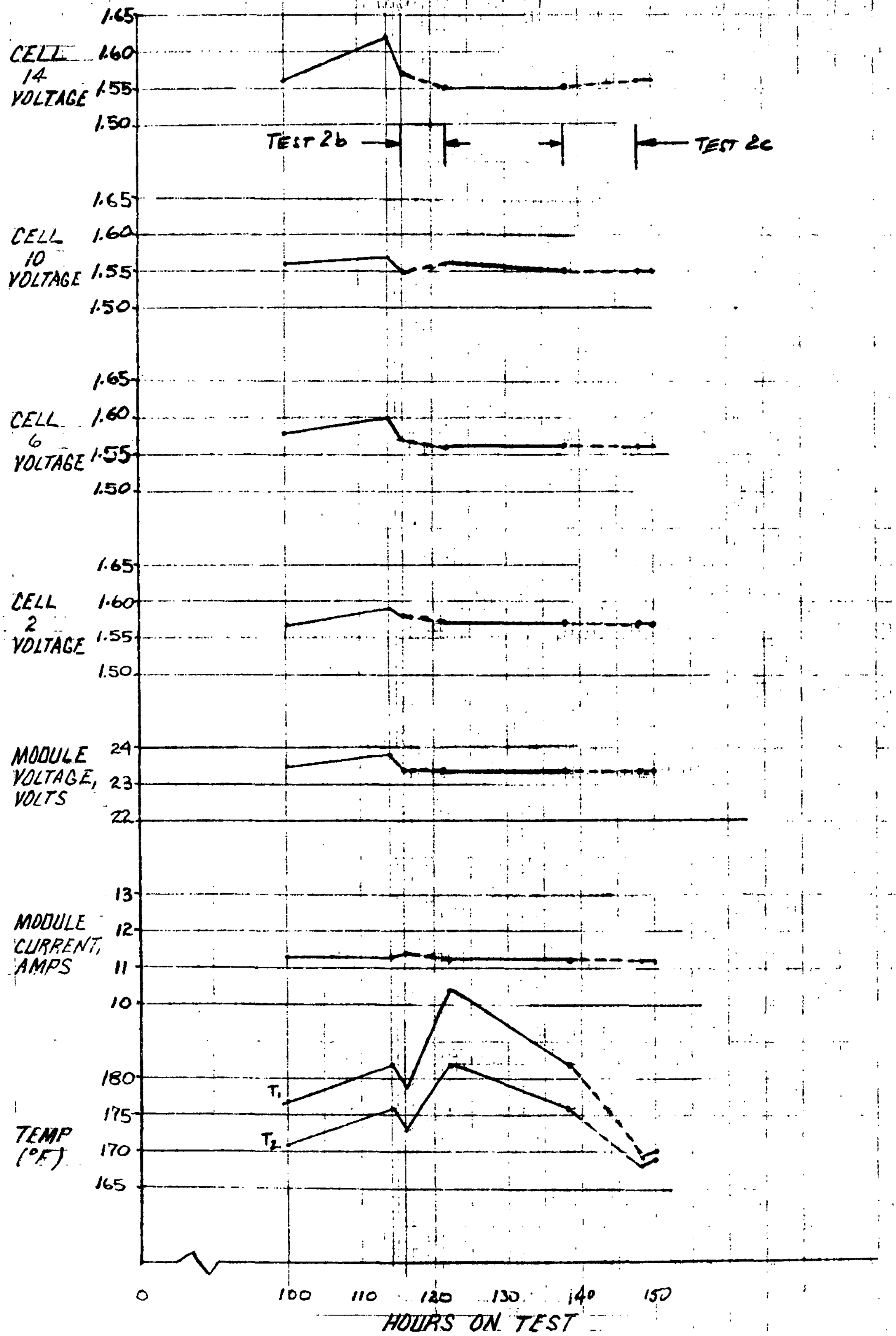


FIGURE 5-13 continued

TEST 2a
TEST BENCH #1

MODULE VOLTAGE VS CURRENT/CURRENT DENSITY
AVERAGE CELL VOLTAGE VS CURRENT/CURRENT DENSITY

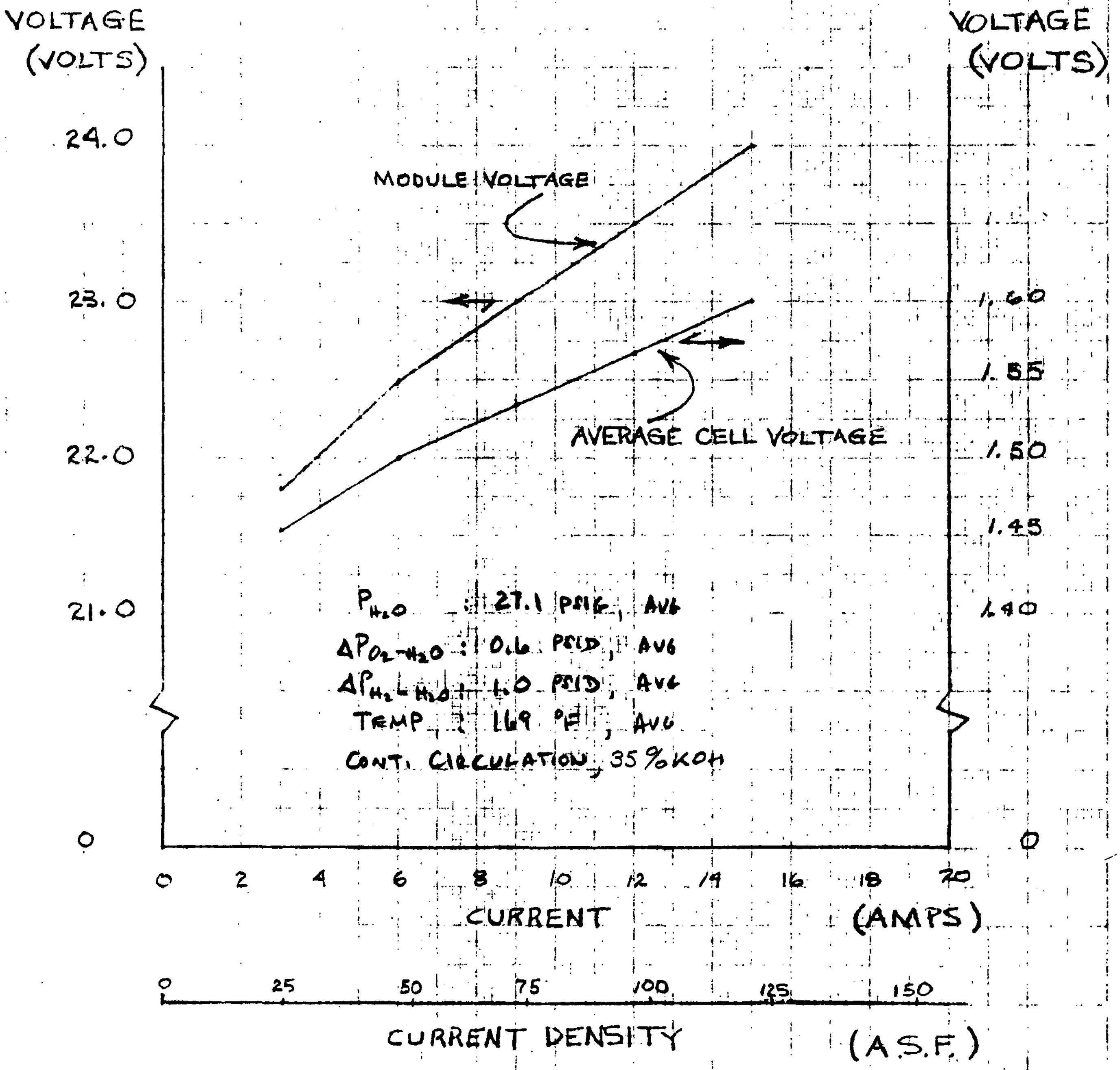
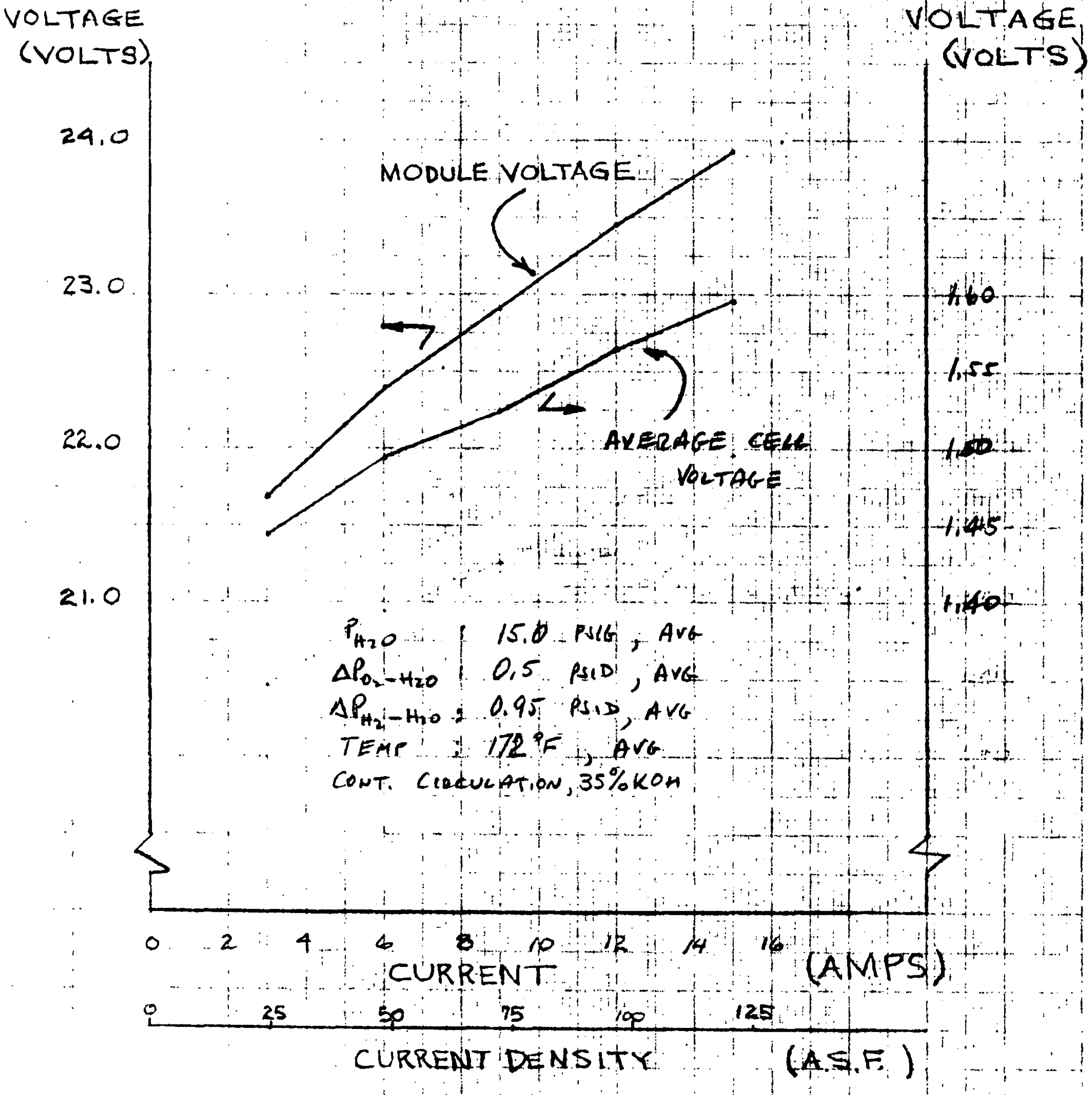


FIGURE 5-14 MODULE #4 VOLTAGE VS CURRENT AT NOMINAL OPERATING CONDITION

TEST 2b
TEST BENCH #1

MODULE VOLTAGE VS. CURRENT/CURRENT DENSITY
AVERAGE CELL VOLTAGE VS CURRENT/CURRENT DENSITY



P_{H_2O} : 15.0 PSIG, AVG
$\Delta P_{O_2-H_2O}$: 0.5 PSID, AVG
$\Delta P_{H_2-H_2O}$: 0.95 PSID, AVG
TEMP : 172 °F, AVG
CONT. CIRCULATION, 35% KOH

FIGURE 5-15 MODULE #4 VOLTAGE VS CURRENT AT 15 PSIG SYSTEM PRESSURE

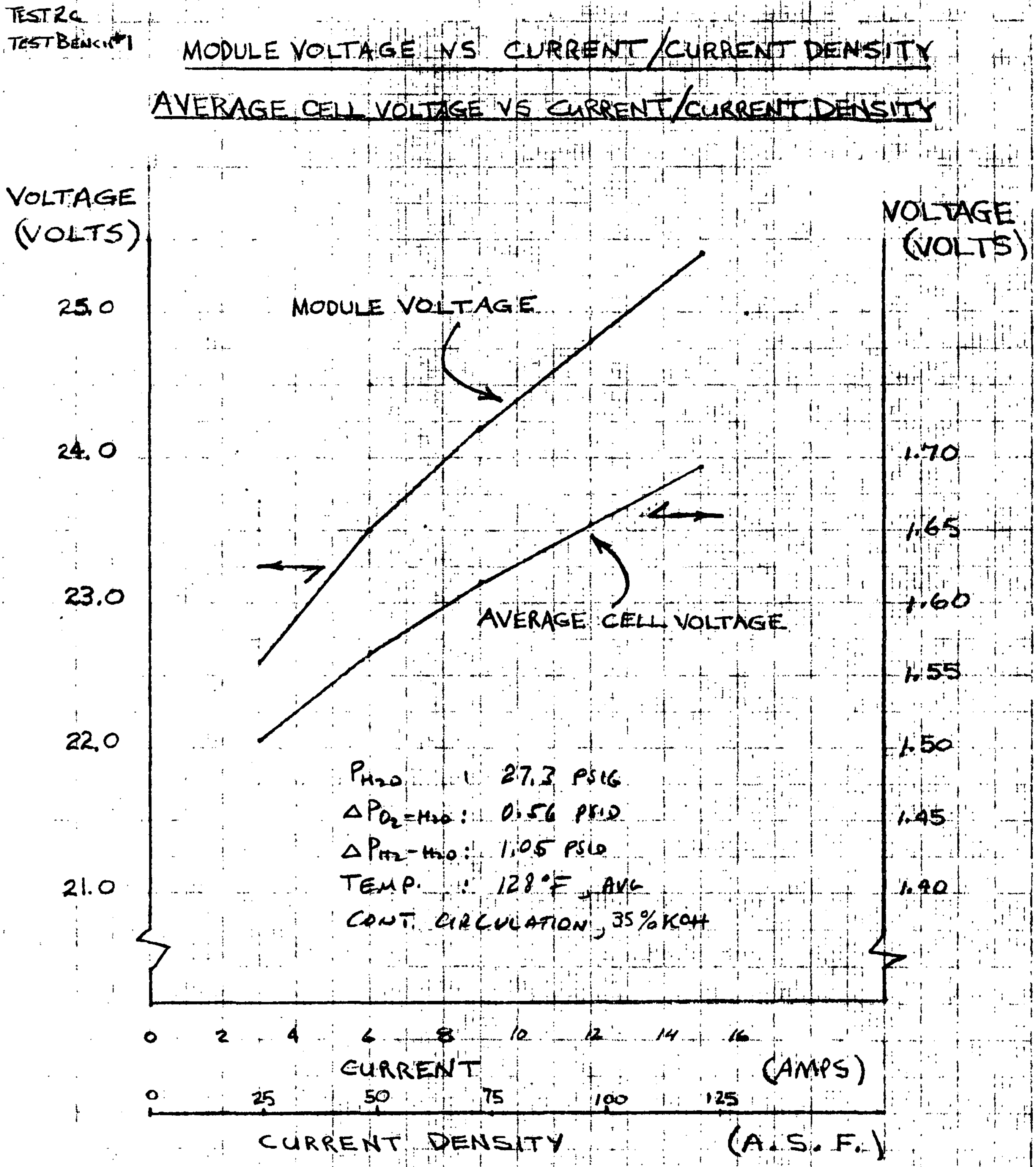


FIGURE 5-16 MODULE #4 VOLTAGE VS CURRENT AT 128F SYSTEM TEMPERATURE (AVERAGE)

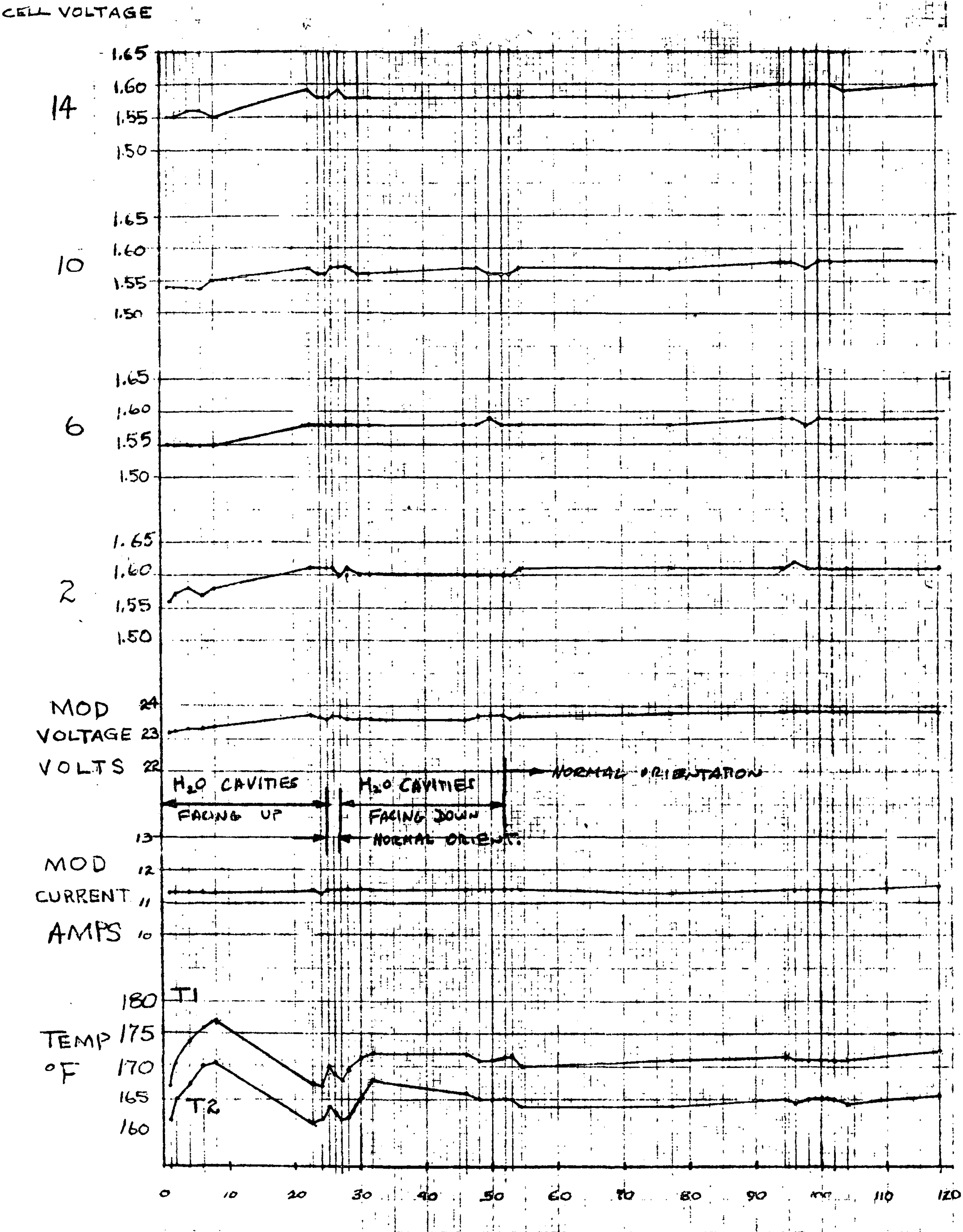


FIGURE 5-17 MODULE #5 ADVERSE ORIENTATION TEST

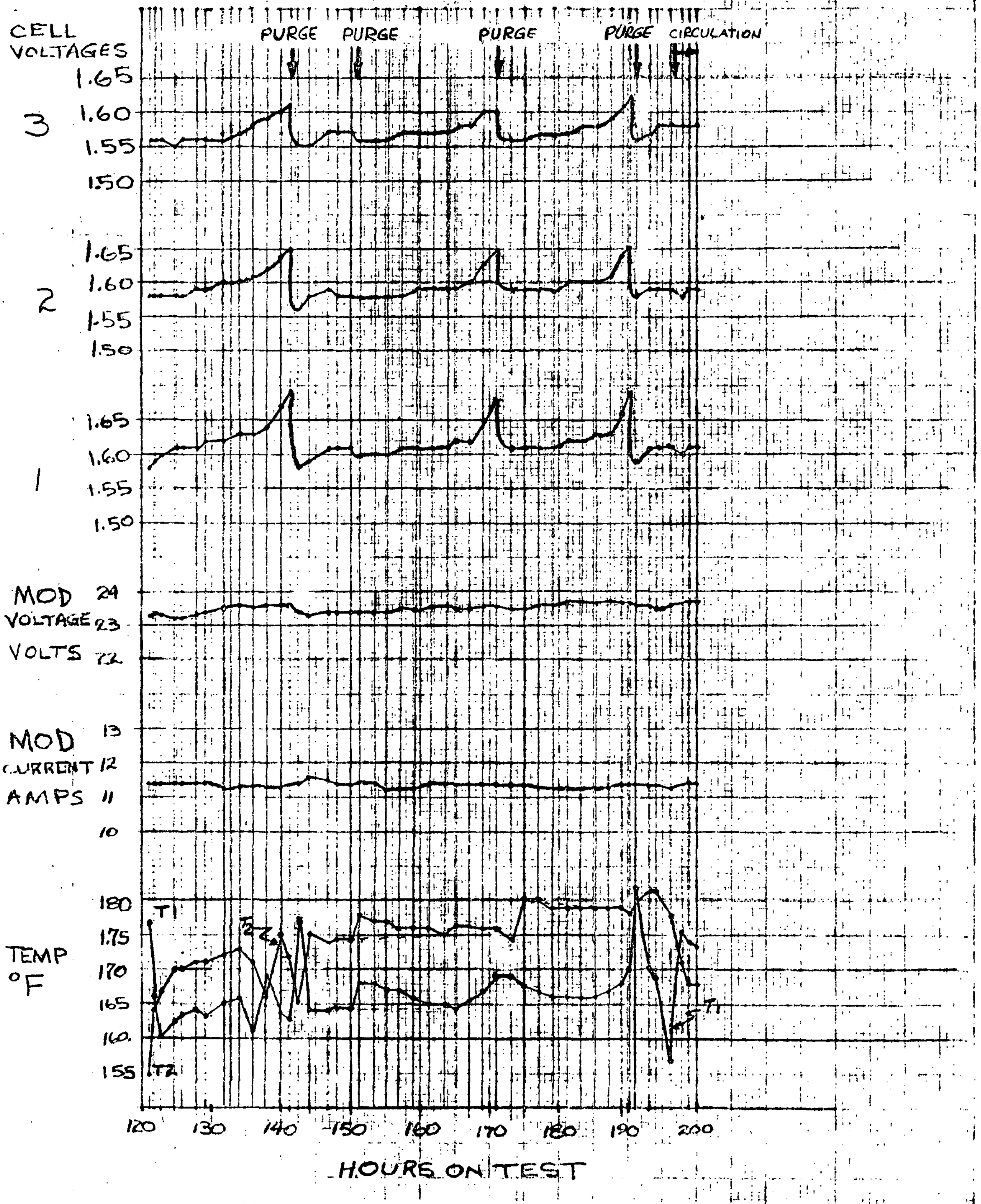


FIGURE 5-18 MODULE #5 STATIC WATER FEED MODE

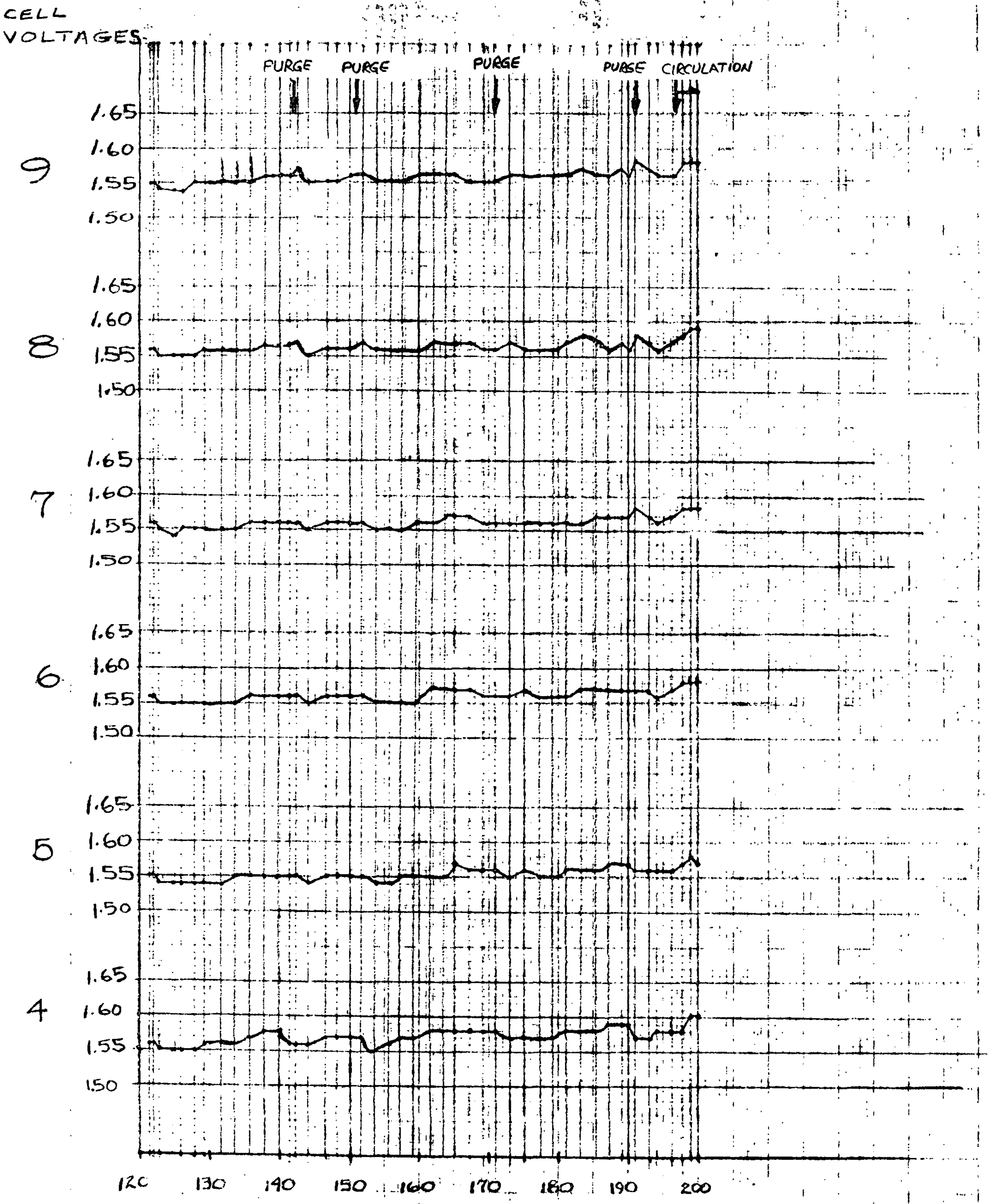


FIGURE 5-18 continued

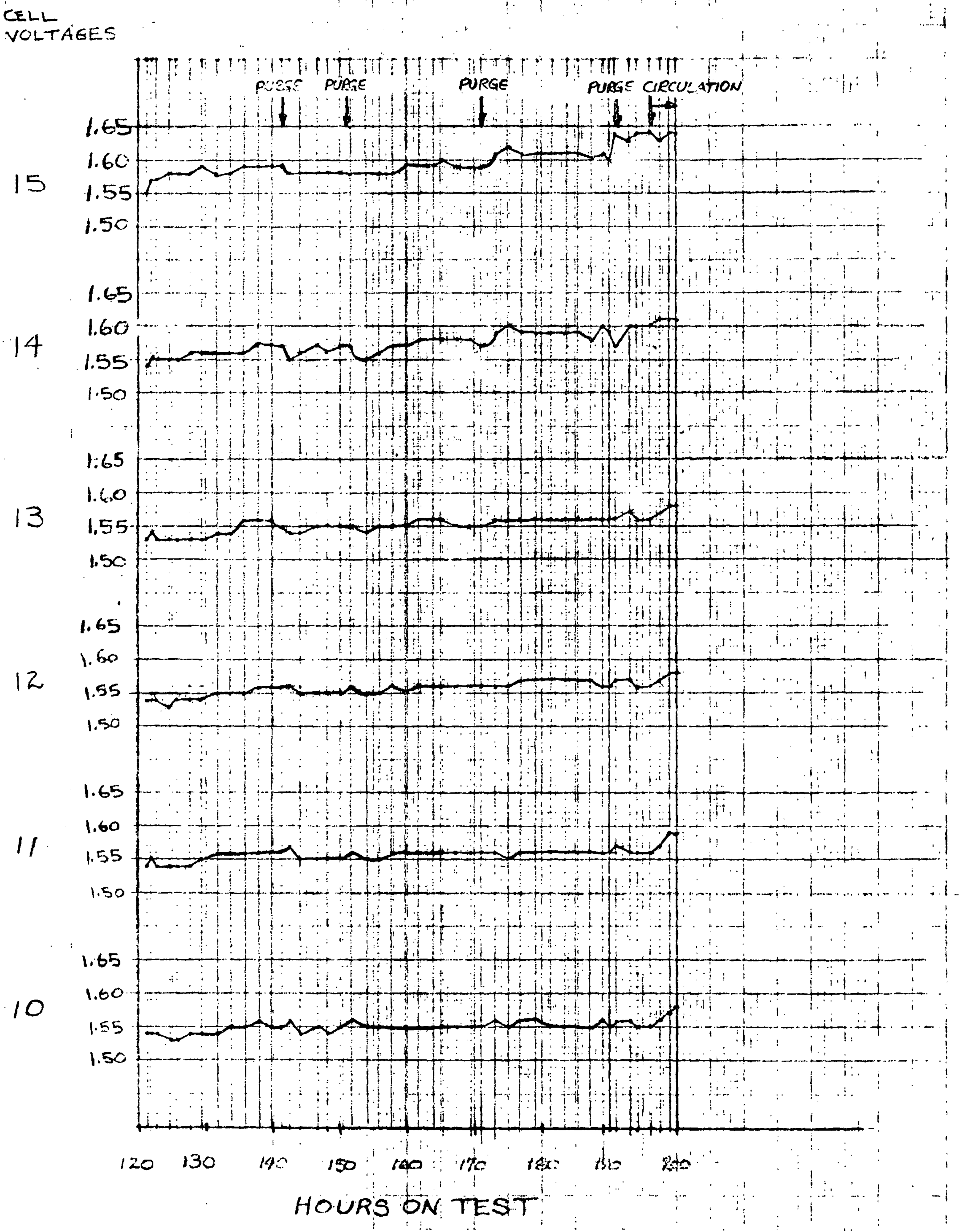


FIGURE 5-18 continued

of static water feed operating mode for the module. The purge times were indicated on the figure. Figure 5-19 shows pressure drop as a function of flow rate through the water cavity feed compartments. These flow tests were conducted prior to the acceptance/characterization tests and were then repeated under identical conditions after the 100-hour acceptance test.

One significant problem was encountered during the testing. During the last 50 hours of the 150-hour acceptance/characterization test of Module #4, a decided increase in gassing rate was observed. Initially a rate of 80 to 90 scc of gas was generated per hour. After the first 100 hours of operation this rate increased to a level of 200 scc. Upon removal of the module insulation an area of KOH leakage was identified near the turn-around plate heater tab between cell #15 and the turn-around plate. Some of the polysulfone cell material appeared to have melted in this area. Stray electrolysis between the interior of the module and the turn-around plate heater tab could be observed when water was sprayed onto the leakage area. A further 6-hour test was conducted to re-establish leakage rate after removal of the KOH salt at the leakage area. The gassing rates found after clean-up were 100 scc per hour. The module was returned to MDAC with a recommendation that a module repair should be undertaken. No other problems were encountered during any of the module or cell testing.

5.3 Cell Testing at Life Systems, Inc.

Testing was performed at LSI on two individual water electrolysis cells. The two cells tested were cell EA-135, a 1968 design version, and cell EA-235, a 1970 design version. A special test setup was employed for the single cell tests. This setup allowed highly accurate testing because it was specifically tailored to use a Kordesch-Marko Bridge for determining anode, cathode and ohmic potentials of a cell.

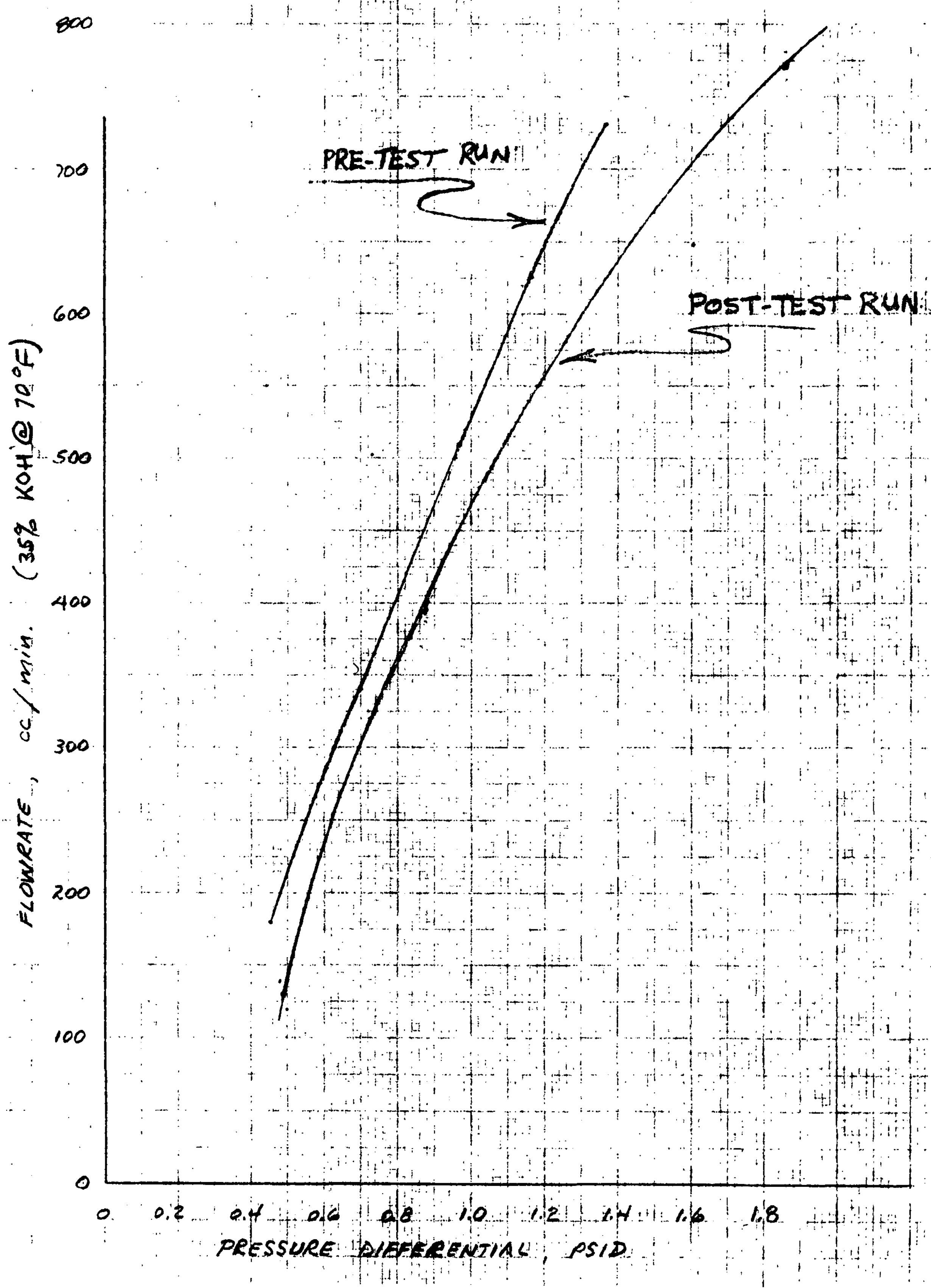


FIGURE 5-19 MODULE #5 FLOW RATE VS PRESSURE DROP THROUGH H_2O CAVITIES

5.3.1 Test Procedures and Facilities

Figure 5-20 is a schematic of the single cell test set-up. The current was regulated by a Kordesch-Marko Bridge enabling measurements of half cell potentials and of the potential drop due to internal resistance. The Kordesch-Marko Bridge accomplished this by utilizing a current interrupting technique (60 Hz). During current interruption that portion of total cell potential due to internal resistance would drop off immediately as current was stopped. The remaining value of the cell potential was that due to cell polarizations. By storing the potentials on capacitors and subtracting polarization from total potentials, the value for ohmic potential was obtained. By use of a reference electrode, the Kordesch-Marko Bridge enabled measurements of half cell reaction potentials, i.e., anode and cathode potentials.

In the single cell test set-up, both H_2 and O_2 pressures were regulated individually by needle control valves, V1 and V2, while the pressures were read on P1 and P2, respectively. Traps located in both product gas streams acted as condensers and prevented moisture from affecting the pressure control valves. Bubblers served as flow indicators. A gear pump was used to circulate electrolyte through the cell and through a 1500 ml electrolyte reservoir. Reservoir temperature was maintained by a hot plate and measured with a mercury thermometer. Electrolyte circulating rate was controlled by needle valve V3, and the circulating loop pressure measured by gage P3. Plumbing connections are made via 0.635 cm (1/4 in) OD vinyl tubing. Oxygen exhaust temperature was measured with an immersion thermocouple in the O_2 exhaust stream. Thermocouple output was read on a potentiometer. Cell temperature was maintained via a 28 volt power supply connected to the two heater tabs on the single cell and/or by circulating heated KOH with its temperature controlled by the hot plate. Gaseous flow rates were measured with a wet test meter connected to the vent tube from the bubblers in both the H_2 and O_2 vent lines. The H_2O consumed was replaced into the KOH reservoir as required. To prevent CO_2 contamination of the KOH due to decreases in volume caused by H_2O consumption or contractions during cooling, an Ascarite-Drierite cartridge was placed in the vent line to the KOH reservoir.

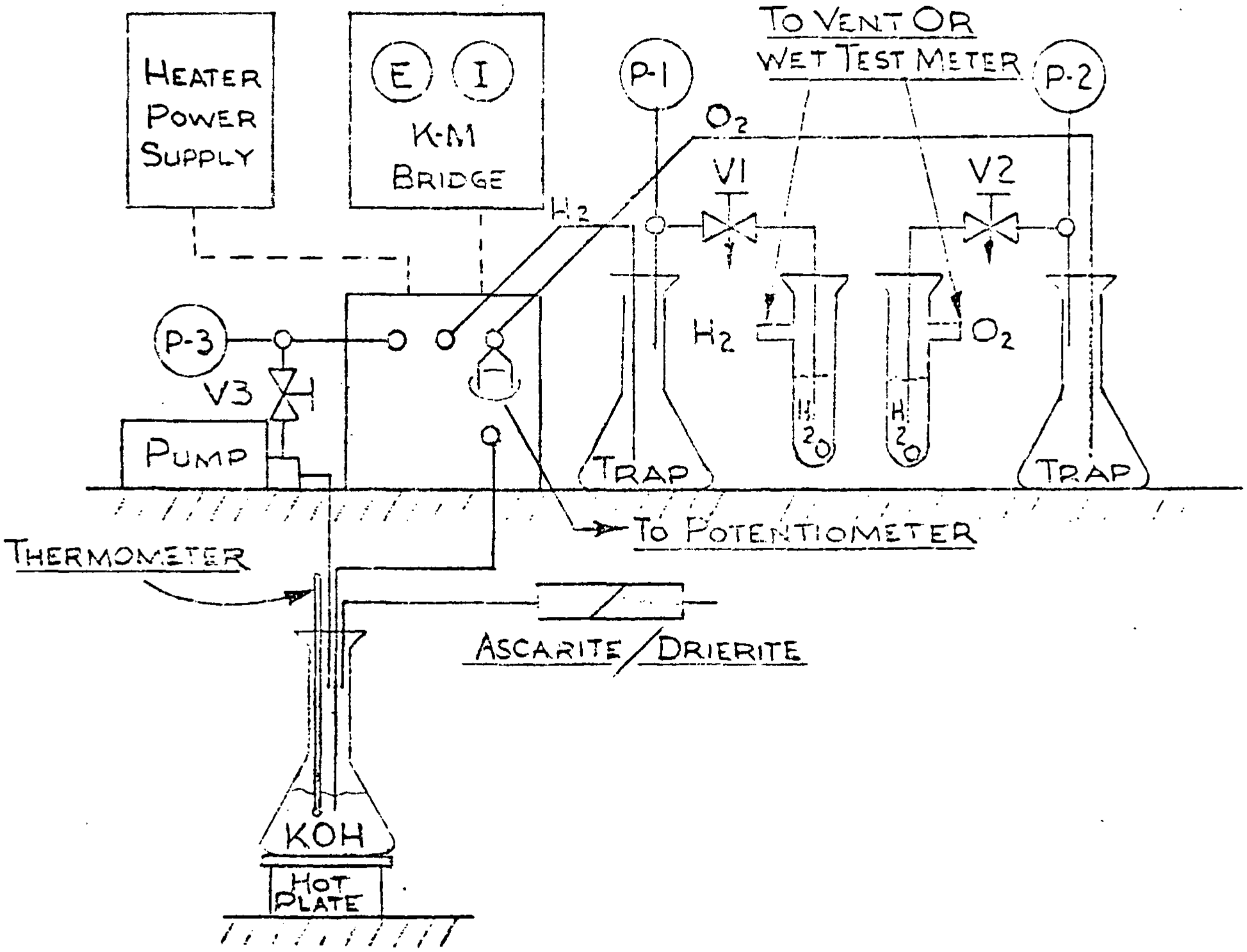


FIGURE 5-20 SINGLE CELL TEST BENCH SCHEMATIC

To fulfill the test objectives of the single cell test program, the experimental testing was divided into four distinct experiments. Each of the four experiments was performed on both the 1968 cell design and the 1970 cell design. The disassembly and part inspection of a single 1968 version cell was performed on a nonoperating cell since inspection of components meant destruction of the cell.

Experiment #1 was conducted to determine the effects of current variation on cell potentials. Besides overall terminal cell potential and ohmic potential, the effects of current variations on anode and cathode potentials were also investigated for the 1968 cell. The effect of current on cell potentials for the 1970 version was limited to terminal cell and ohmic potentials since half cell potentials require the presence of a reference electrode. To add a reference electrode to a single cell necessitates drilling into the cell housing to acquire access to the cell matrix. Since 1970 cells were of a limited availability, this type of testing was limited to the 1968 cell design.

Experiment #2 determined the effect of changes in the pressure differential between the H_2 and O_2 compartments on cell potentials.

Experiment #3 determined the effect of overpressurizing the H_2 compartment with respect to the H_2O feed compartment to investigate possible effects on H_2O transportation rate from the feed matrix to the cell matrix. Overpressurization of the H_2-to-H_2O compartments could cause gas bubbles to be permanently lodged in the matrix pores and matrix support perforations. This could inhibit H_2O transportation rates even after the overpressure differential was removed.

Experiment #4 involved observing cell operation at voltages above 1.7 volts (an upper limit specified by the cell's original manufacturer). Operating above 1.7 volts was achieved by increasing the cell current.

Following the four experiments on each individual cell was the disassembly of a 1968 cell design. The disassembly of the cell involved cutting the cell at strategic locations to enable measurements of the various layers of bonded polysulfone sheets. Since this necessitates destruction of the cell, an inoperative cell was used to measure and evaluate cell components and parts.

5.3.2 1968-Design Cell

To perform Test #1 for the 1968 design required physical access to the cell matrix to connect a reference electrode (to determine anode and cathode potentials). A hole, 0.478 cm (3/16 in.) diameter, was drilled from the anode side of the cell to the portion of the asbestos cell matrix that extends beyond the anode electrode. A circular electrode, slightly less than 0.478 cm (3/16 in.) diameter and made of platinized screen, was placed securely against the cell matrix asbestos. A flat ended fitting isolated from the electrode via a teflon disc pressed the reference electrode against the cell matrix. The inner passages of this metal fitting were isolated from the reference electrode lead with teflon tubing. A plastic tee connected to the metal fitting through plastic tubing served as a lead wire passage through one leg of the tee and H_2 reference gas supply through the other leg of the tee. Figure 5-21 shows a cross-section of the reference electrode subassembly.

Prior to inserting the reference electrode into the cell, the exposed cell matrix within the 0.478 cm (3/16 in.) diameter hole was wetted with 35% KOH solution (equivalent to original matrix charge) to insure electrical continuity.

In Experiment #1 the various cell potentials were measured as a function of increasing current, hence increasing current density. Experiment #4 called for operating the cell at a voltage level above 1.7 volts. Experiment #4, therefore, was a natural continuation of experiment #1 and the two were performed during one single day of testing without interrupting cell operation. Data obtained, therefore, from Experiments #1 and #4 are presented on common curves.

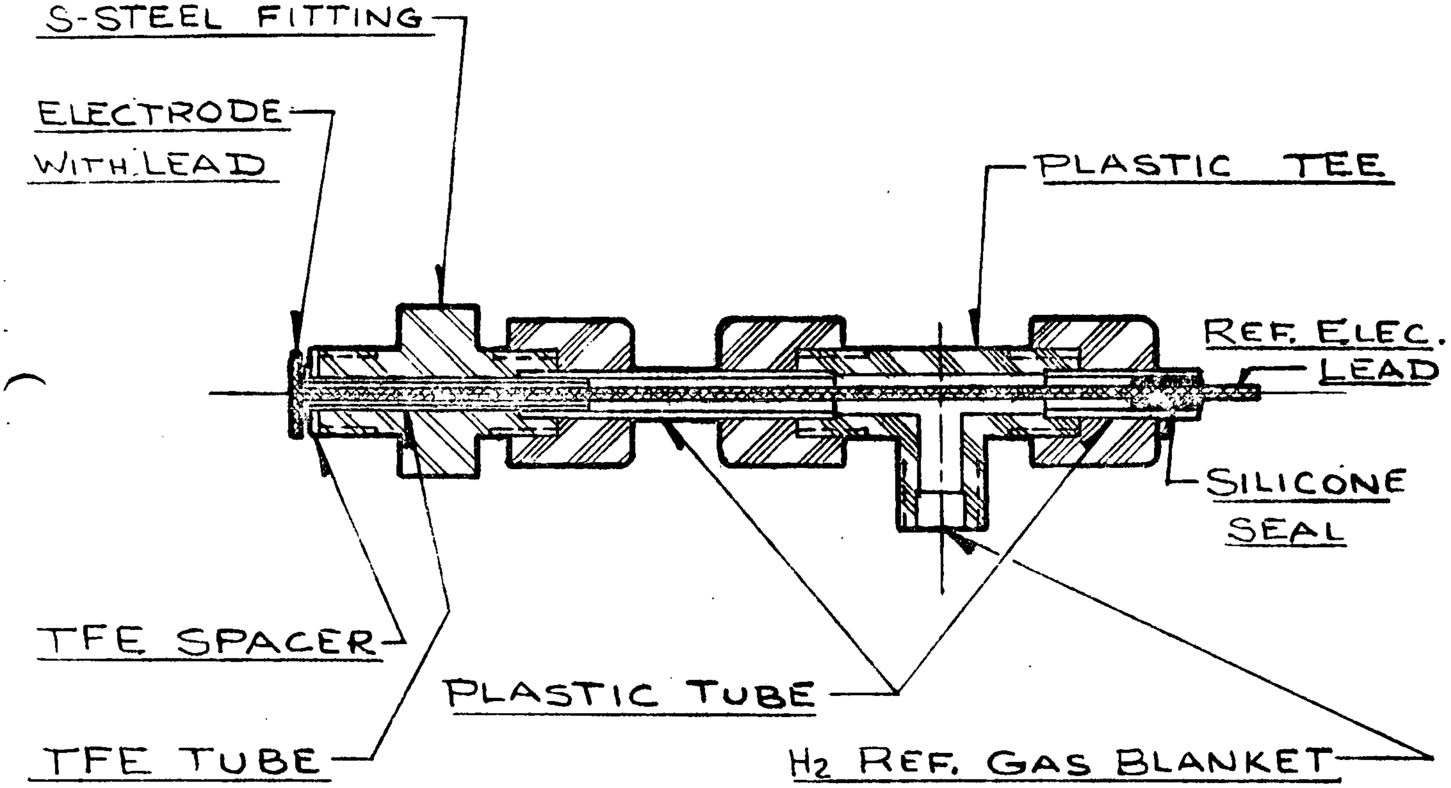


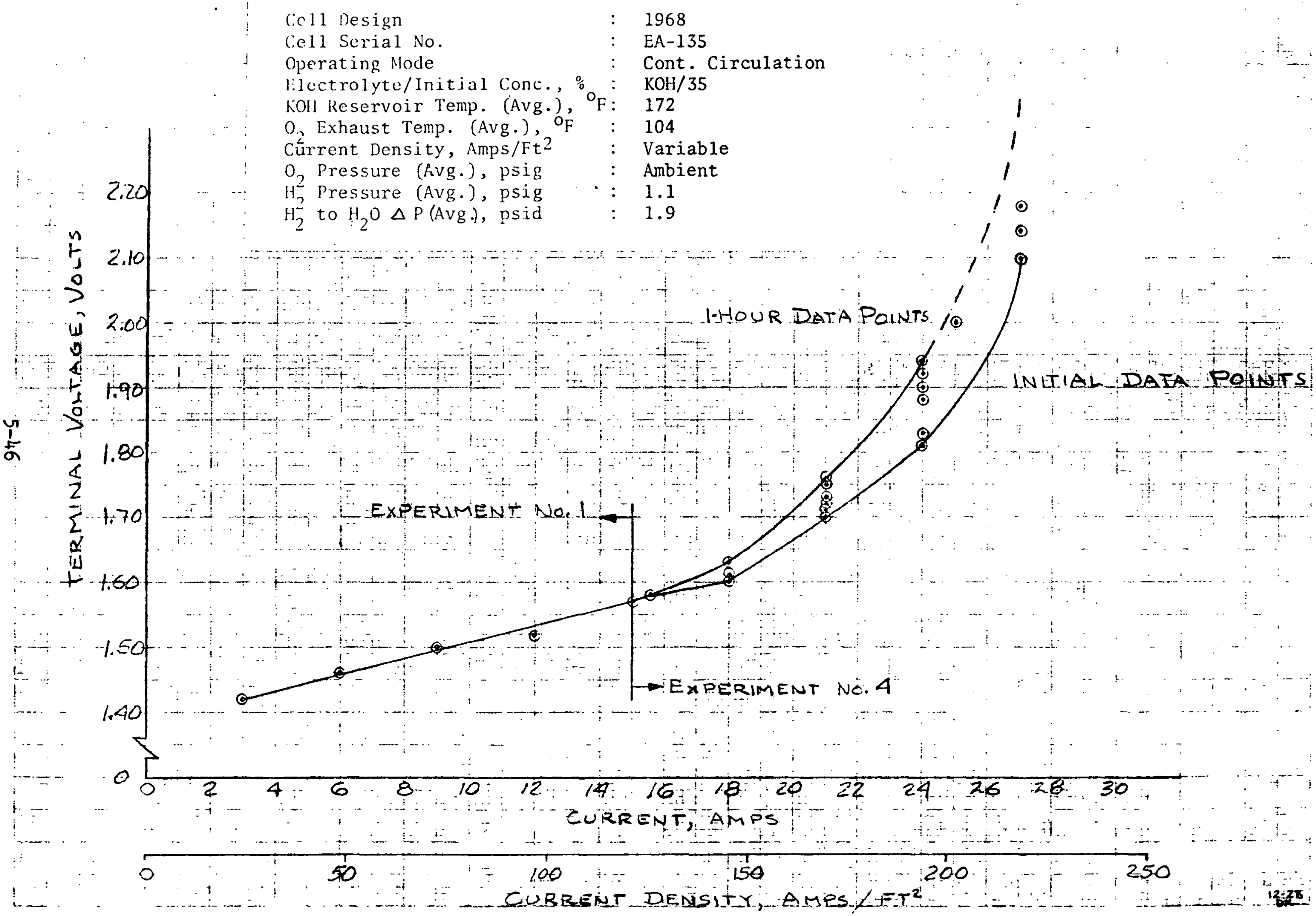
FIGURE 5-21 REFERENCE ELECTRODE SUBASSEMBLY

For Experiment #1 the cell current was varied from 3 to 15 amperes in three ampere increments. Under Experiment #4 the current was further increased in three ampere increments until cell voltage exceeded 1.7 volts. Once the cell voltage exceeded 1.7 volts, the current was further increased in three ampere increments until an accelerated rise in cell voltage with respect to time was observed. Cell current was then lowered to 12 amperes.

Figure 5-22 shows terminal cell voltage versus current and current density for the 1968 design cell, EA-135. The ranges of Experiments #1 and #4 are indicated. All data was taken during continuous circulation of KOH through the H_2O cavities. All operating parameters are indicated on Figure 5-22.

The performance obtained under Experiment #1 (current from 3 through 15 amperes) is typical of a cell operating under steady-state conditions. The slope obtained in this region of current is approximately constant and equal to 12.5 mv/ampere. No voltage increase with time (1 hour) at any one current setting was observed. At 15 amperes (130 mA/cm^2) (121 A/ft^2) the cell voltage was 1.57 volts.

The performance of the cell at a current level above 15 amperes shows a marked increase in slope. Also, an increase in cell voltage is observed from the initial time in which the current level was established to the end of a 1 hour increment at which time the current was changed to a new level. These observations are typical of a cell that is reaching its operational limit with respect to current density at the given set of operating conditions. The level of 1.7 volts was reached at 21 amperes (182 mA/cm^2) (169 A/ft^2). Current was further increased to a level of 27 amperes or a current density of approximately 237 mA/cm^2 (220 A/ft^2), where the voltage level increased rapidly with time (from an initial value of 2.10 volts) which point Experiment #4 was terminated to prevent cell damage.



Cell Design : 1968
Cell Serial No. : EA-135
Operating Mode : Cont. Circulation
Electrolyte/Initial Conc., % : KOH/35
KOH Reservoir Temp. (Avg.), °F : 172
O_2 Exhaust Temp. (Avg.), °F : 104
Current Density, Amps/Ft^2 : Variable
O_2 Pressure (Avg.), psig : Ambient
H_2 Pressure (Avg.), psig : 1.1
H_2 to H_2O Δ P (Avg.), psid : 1.9

FIGURE 5-22 TERMINAL VOLTAGE VERSUS CURRENT, 1968 CELL,
EXPERIMENTS #1 AND #4

The critical observation in the data under Experiment #4 is the voltage versus current slope increase with increasing current, which shows the cell to be approaching its limiting current density level. After the cell had reached 2.18 volts after operating at 27 amperes for 20 minutes, its current level was returned to 12 amperes and its voltage dropped to 1.62 within a 20 minute period. At restart of the cell on the following day the cell showed a voltage of 1.53 volts at 12 amperes as compared to 1.52 volts the previous day during Experiment #1. It can therefore be concluded that the cell recovered within its typical operational band at design amperage.

The data obtained during Experiments #1 and #4 is also presented in Figure 5-23. This figure shows cell voltage versus operating time as a function of current levels. The increasing slopes of current versus time beyond the 15 amperes mark shows the cell reaching it operational limit. Also shown is the recovery after 27 ampere operation. In addition to terminal voltage, the cathode, anode and iR drop potentials were recorded during Experiment #1 (thru 15 amperes). The variations in these potentials are shown in Figure 5-24. Both cathode and anode potentials show nearly constant slope variation with respect to current. A slight increase in slope can be noticed in the iR drop potential as might be expected due to concentration increases and resulting electrolyte volume reductions. No unusual variations are noted and the cell is well within its operating capability limits over the current range investigated.

IR free potentials and iR drop potentials were not scheduled to be taken during Experiment #4. This was in anticipation of the power output limitations of the Kordesch-Marko Bridge above 15 amperes. To operate the cell at current levels greater than 15 amperes necessitated using a separate power supply; however, the reference to <u>terminal</u> anode and reference to <u>terminal</u> cathode potentials (containing iR drop values) could still be read on the Kordesch-Marko Bridge meters. Figure 5-25 shows these various cell potentials as a function of current level. The voltage is presented with respect to the reference electrode potential. For experiment #1, both terminal and iR free potentials are shown through 15 amperes.

Cell Design	:	1968
Cell Serial No.	:	EA-135
Operating Mode	:	Cont. Circulat.
Electrolyte/Initial Conc., %	:	KOH/35
KOH Reservoir Temp. (Avg.), ^oF	:	172
O_2 Exhaust Temp. (Avg.), ^oF	:	104
Current Density, Amps/Ft^2	:	Variable
O_2 Pressure (Avg.), psig	:	Ambient
H_2 Pressure (Avg.), psig	:	1.1
H_2 to H_2O ΔP (Avg.), psid	:	1.9

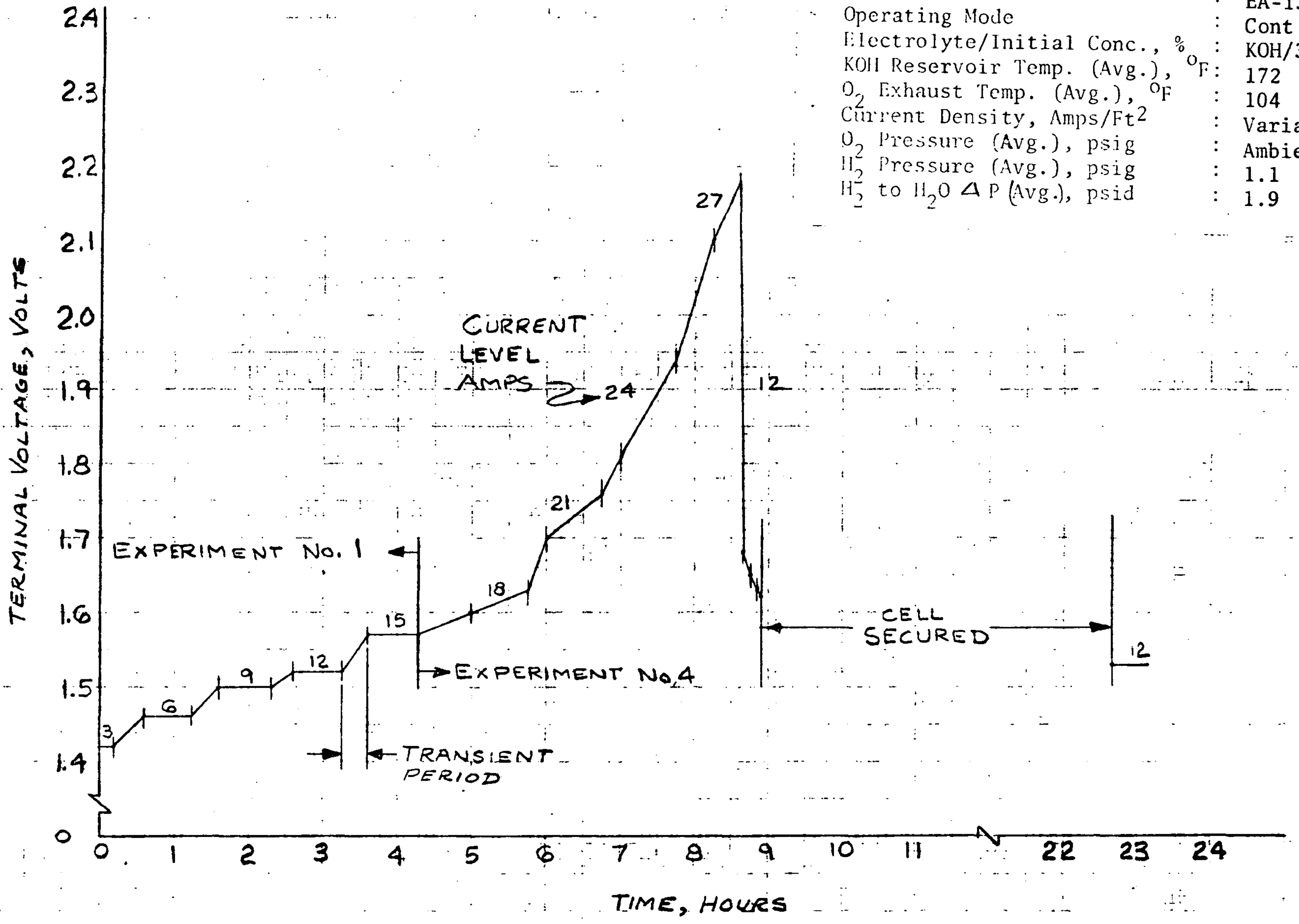


FIGURE 5-23 TERMINAL VOLTAGE VERSUS TIME, 1968 CELL, EXPERIMENTS #1 AND #4

12-23 DK

Cell Design	: 1968
Cell Serial No.	: EA-135
Operating Mode	: Cont. Circula
Electrolyte/Initial Conc., %	: KOH/35
KOH Reservoir Temp. (Avg.), °F	: 172
O_2 Exhaust Temp. (Avg.), °F	: 104
Current Density, Amps/Ft^2	: Variable
O_2 Pressure (Avg.), psig	: Ambient
H_2 Pressure (Avg.), psig	: 1.1
H_2 to H_2O Δ P (Avg.), psid	: 1.9

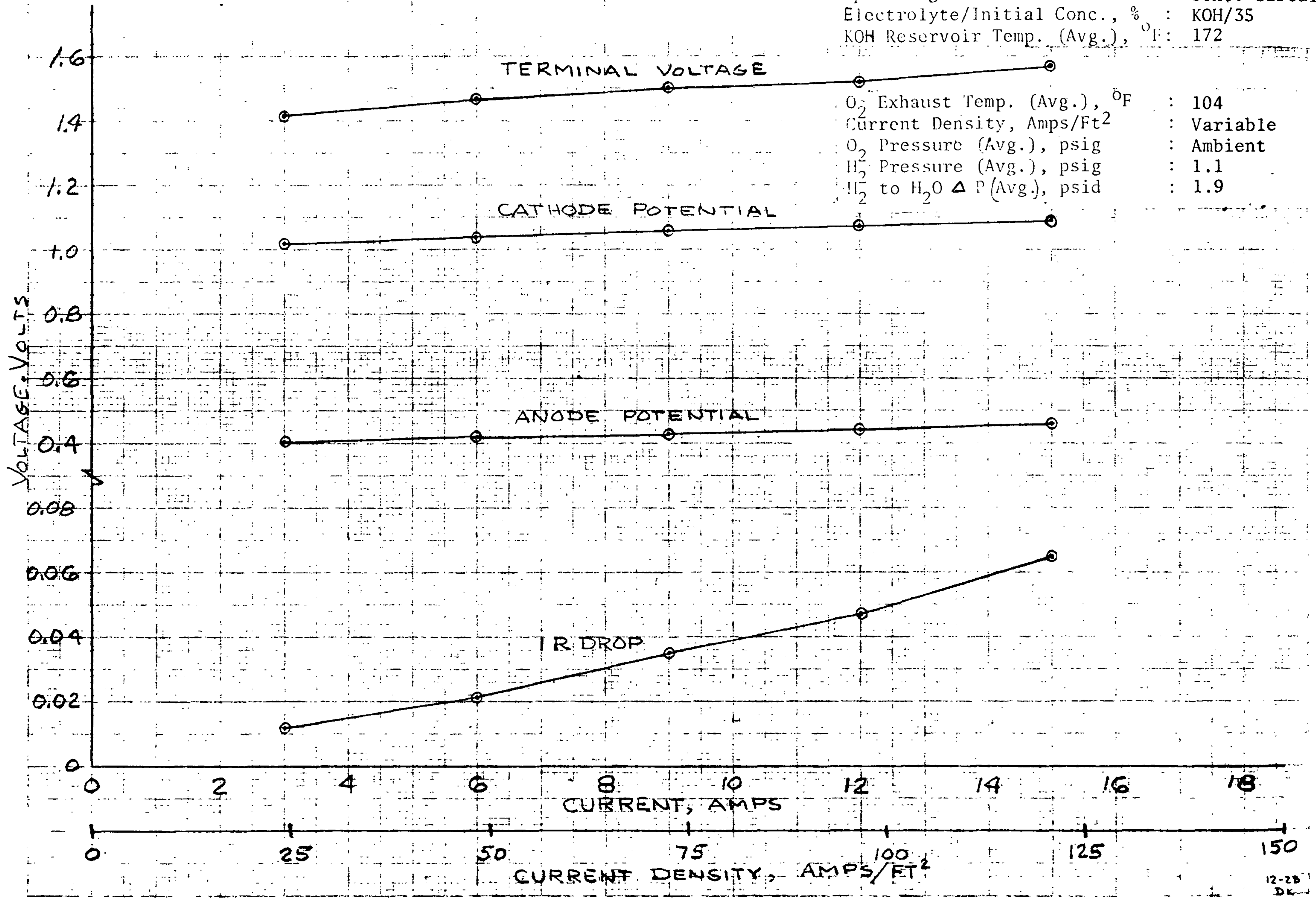
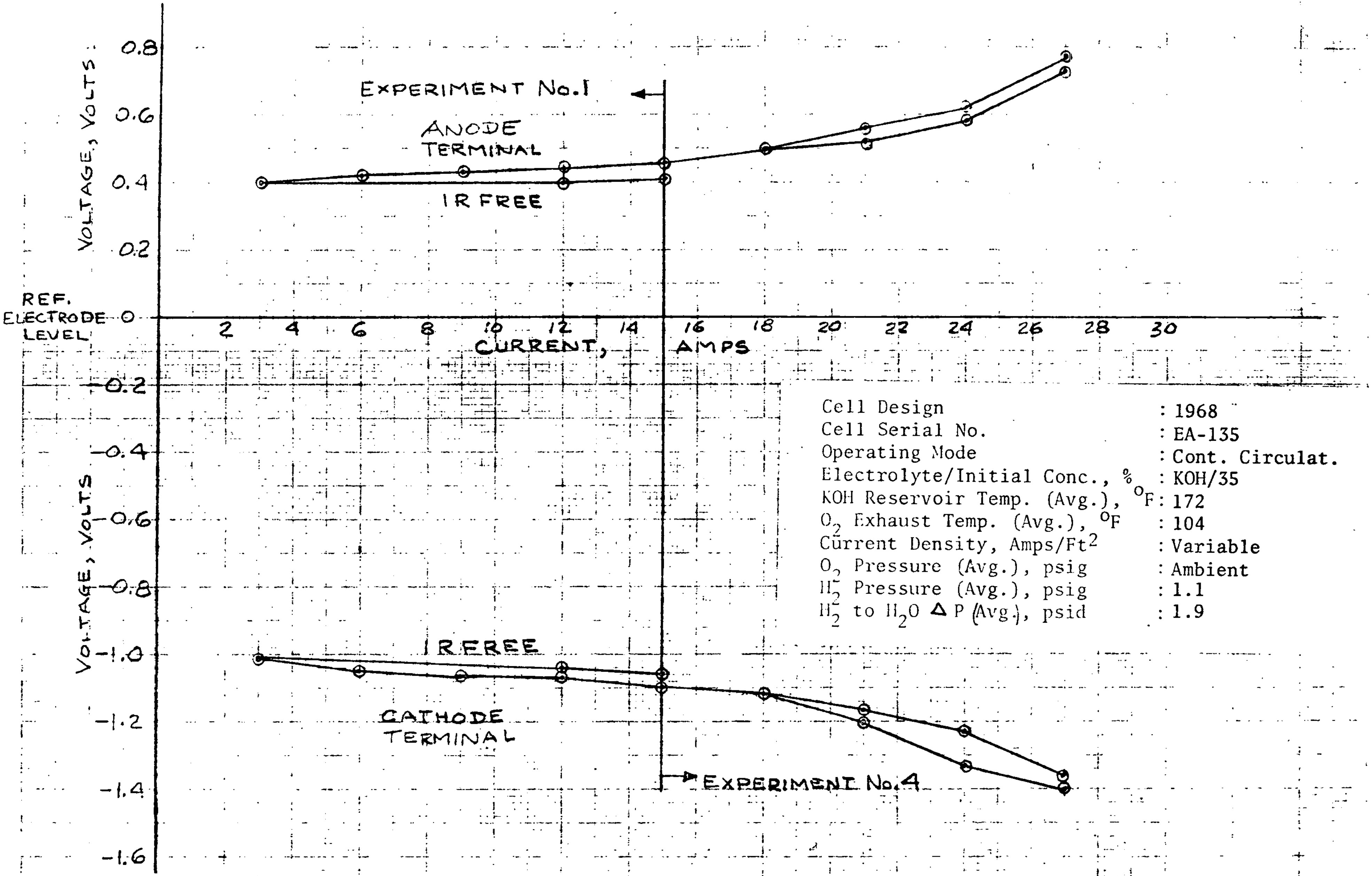


FIGURE 5-24 CELL POTENTIALS VERSUS CURRENT, 1968 CELL, EXPERIMENT #1



Cell Design : 1968
Cell Serial No. : EA-135
Operating Mode : Cont. Circulat.
Electrolyte/Initial Conc., % : KOH/35
KOH Reservoir Temp. (Avg.), °F : 172
O_2 Exhaust Temp. (Avg.), °F : 104
Current Density, Amps/Ft^2 : Variable
O_2 Pressure (Avg.), psig : Ambient
H_2 Pressure (Avg.), psig : 1.1
H_2 to H_2O Δ P (Avg.), psid : 1.9

FIGURE 5-25 ANODE AND CATHODE TERMINAL VOLTAGE VERSUS CURRENT, 1968 DESIGN, EXPERIMENTS #1 AND #4

The variation in voltage above 15 amperes is that observed with time (1 hour) as discussed above. The voltage level of the reference electrode is high compared to that typically expected from a reversible H_2 electrode. Typically, one would expect a reference electrode of reversible H_2 closer to the cathode potentials. The level, however, remained constant throughout the experiment and hence can be used without introducing erroneous results. An explanation for its high level is the possibility of H_2 not having saturated all pores and surface areas of the reference electrode. Figure 5-25 shows that increases in terminal voltages are equally due to increases in cathode potential as well as anode potential. As noted above, the iR drop data could not be measured beyond 15 amperes, hence its contribution to cell voltage increases could not be isolated beyond that current level. Based on data obtained in Experiment #1, one could assume the iR drop increases linearly but splits relatively equally between anode and cathode potentials.

Experiment #2 was to measure the effect that varying the H_2-to-O_2 pressure differential has on the individual cell potentials. A range of $\pm 4.13 \times 10^4$ N/m^2 differential (± 6 psid), H_2-to-O_2 ΔP was investigated in 13.9×10^3 N/m^2 (2 psi) increments. The experiment was performed by maintaining constant H_2 and H_2O pressure levels and varying the O_2 pressure level 4.13×10^4 N/m^2 differential (6 psid) above and below the H_2 level. Each differential pressure level was maintained for 30 minutes with data recorded every 10 minutes. All other parameters were maintained constant and their values are indicated on Figures 5-26 and 5-27.

Figure 5-26 shows terminal voltage and anode iR free voltage as a function of H_2-to-O_2 pressure differential. At each pressure differential, the range in voltages (as observed) is indicated with the average values used to plot the actual curve. The results show that with a H_2 pressure below the O_2 pressure the terminal voltage increases. This rise in terminal voltage is approximately 25 mv when changing the H_2-to-O_2 pressure differential from $+ 4.13 \times 10^4$ to -4.13×10^4 N/m^2 differential (+6 to -6 psid).

Cell Design	: 1968
Cell Serial No.	: EA-135
Operating Mode	: Cont. Circulation
Electrolyte/Initial Conc., %	: KOH/35
KOH Reservoir Temp. (Avg.), °F	: 171
O_2 Exhaust Temp. (Avg.), °F	: 98
Current Density, Amps/Ft^2	: 91
O_2 Pressure (Avg.), psig	: Variable
H_2 Pressure (Avg.), psig	: 1.0
H_2 to H_2O Δ P (Avg.), psid	: 1.9

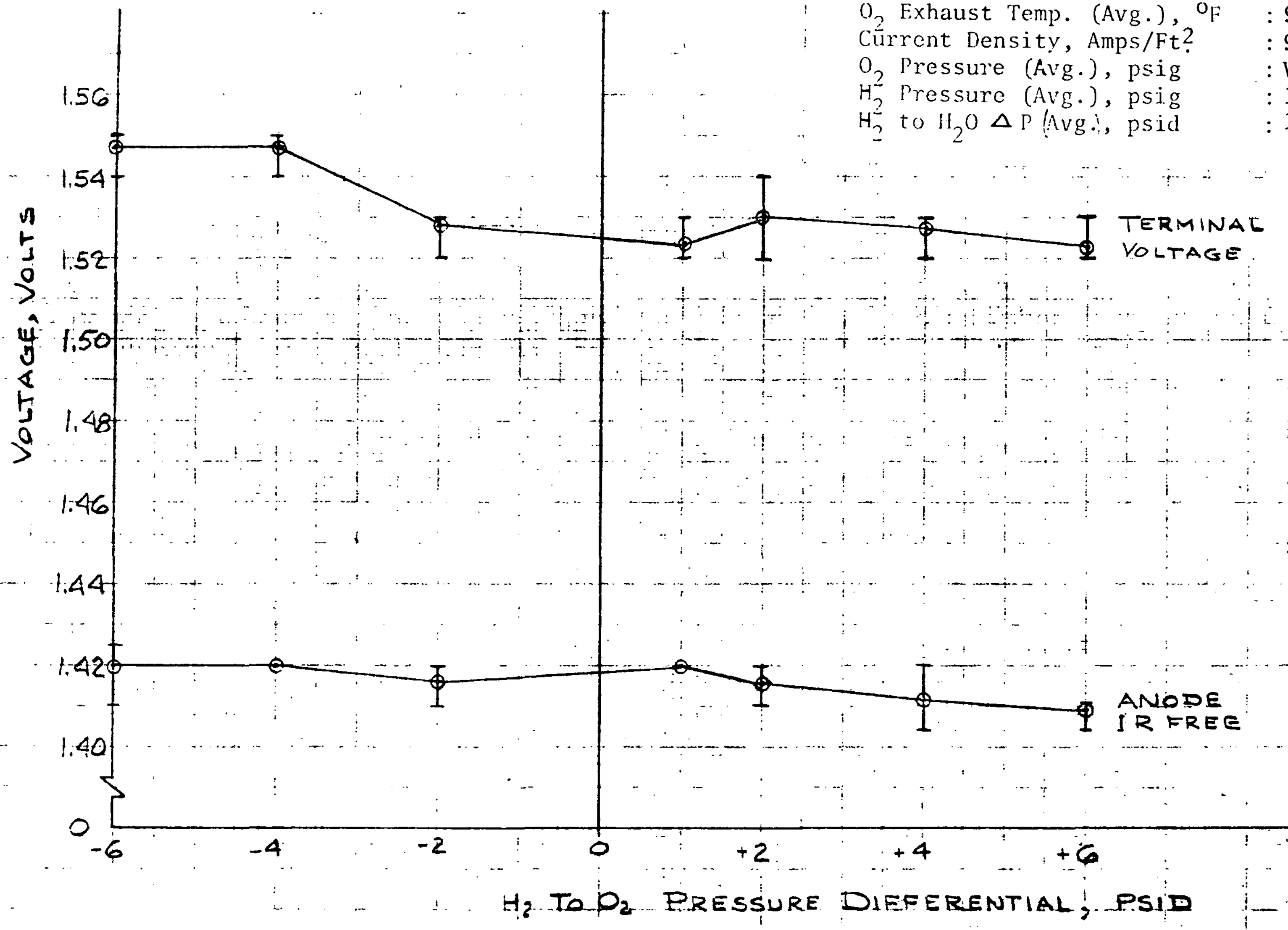


FIGURE 5-26 TERMINAL AND ANODE iR FREE VOLTAGE VERSUS H_2 TO O_2 PRESSURE DIFFERENTIAL, 1968 DESIGN, EXPERIMENT #2

The anode iR free voltage also shows a slightly higher value with the H_2 pressure less than O_2 pressure. Its total change over the range of pressure differentials is 12 mv. Similarly, Figure 5-27 shows ranges in observed cathode iR free and iR drop voltages plotted at each pressure differential level. The apparent higher fluctuations in the cathode iR free and iR drop levels on Figure 5-27 are due to the expanded scales. The maximum change in iR drop was 2 mv while the maximum change in cathode iR free voltage is 8 mv. The iR drop remained very steady with respect to pressure differential. Cathode iR free voltage shows a greater fluctuation than the iR drop voltage. In summary, the data in Figures 5-26 and 5-27 (Experiment #2) show that the effect of pressure differential on a 1968 cell design is relatively minor and may result in only a 25 mv increase when changing the H_2-to-O_2 pressure differential from + 4.13×10^4 to -4.13×10^4 N/m^2 differential (+6 to -6 psid).

During Experiment #3 the H_2-to-H_2O pressure differential was varied over a range of + 10.3×10^3 to + 59.3×10^3 N/m^2 differential (+1.5 to +8.6 psid). Terminal voltage, cathode and anode iR free voltages, and iR drop voltage were recorded for average H_2 to H_2O pressure differentials of 19.3×10^3, 38.5×10^3, 59.2×10^3, 10.3×10^3, and 17.2×10^3 N/m^2 (2.8, 5.6, 8.6, 1.5 and 2.5 psid). The test results are shown in Figures 5-28 and 5-29. The figures indicate the operating conditions at which the test was performed. Figure 5-28 shows terminal voltage and iR free voltage and Figure 5-29 shows iR drop voltage and cathode iR free voltage as a function of H_2-to-H_2O pressure differential. Again, observed test ranges in voltages and pressure differentials are indicated with the average values used for curve plotting. Each pressure level range was maintained for a total duration of 1 hour while recording data at 15 minute intervals.

After returning to a pressure differential of 10.3×10^3 N/m^2 (1.5 psid), the cell was allowed to operate for an additional 2.5 hours to compare before and after voltage levels. Figures 5-28 and 5-29 typically show that the potentials of the cell increased as the H_2-to-H_2O pressure differential

Cell Design : 1968
Cell Serial No. : EA-135
Operating Mode : Cont. Circulation
Electrolyte/Initial Conc., % : KOH/35
KOH Reservoir Temp. (Avg.), °F : 171
O_2 Exhaust Temp. (Avg.), °F : 98
Current Density, Amps/Ft^2 : 91
O_2 Pressure (Avg.), psig : Variable
H_2 Pressure (Avg.), psig : 1.0
H_2 to H_2O Δ P (Avg.), psid : 1.9

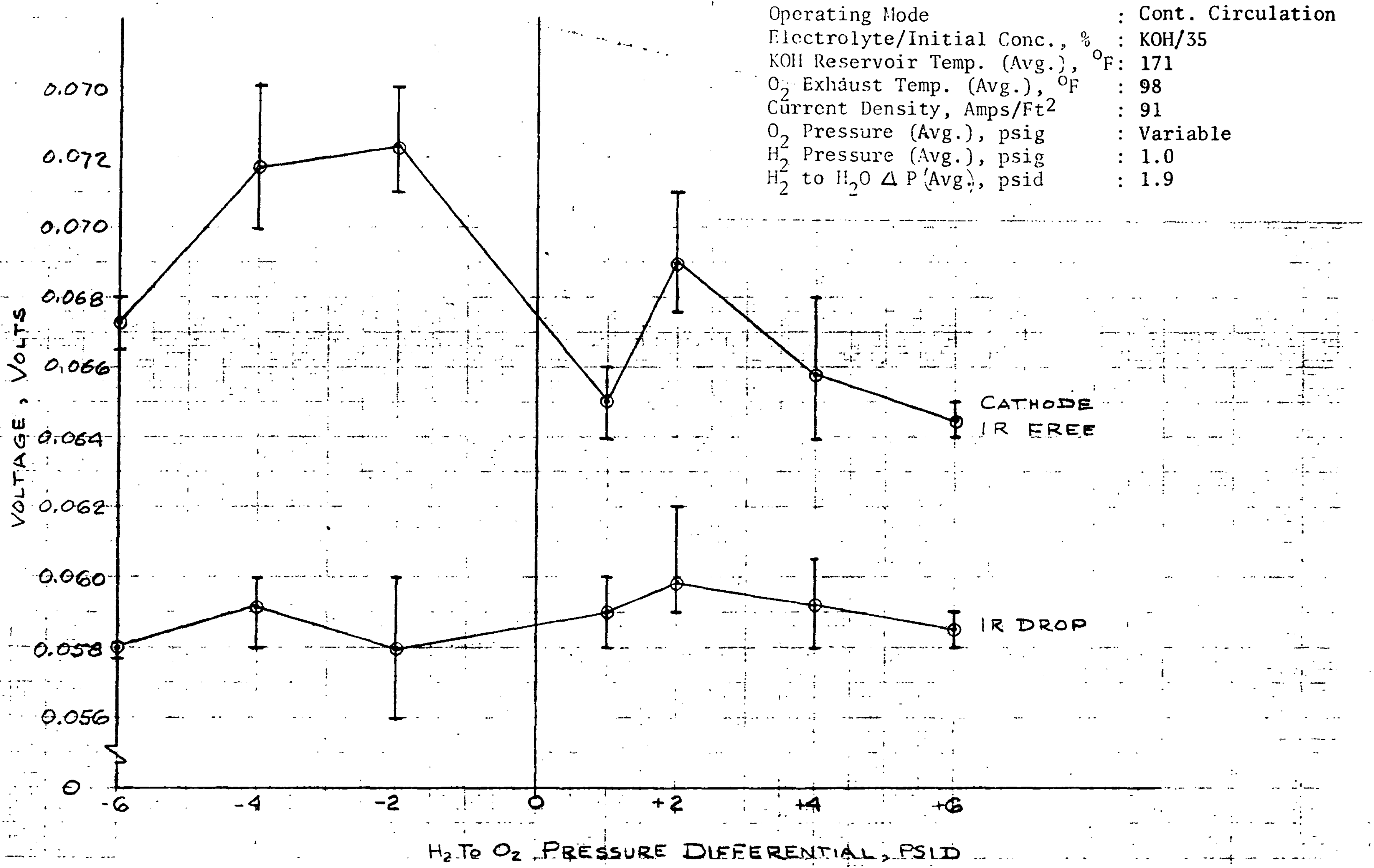
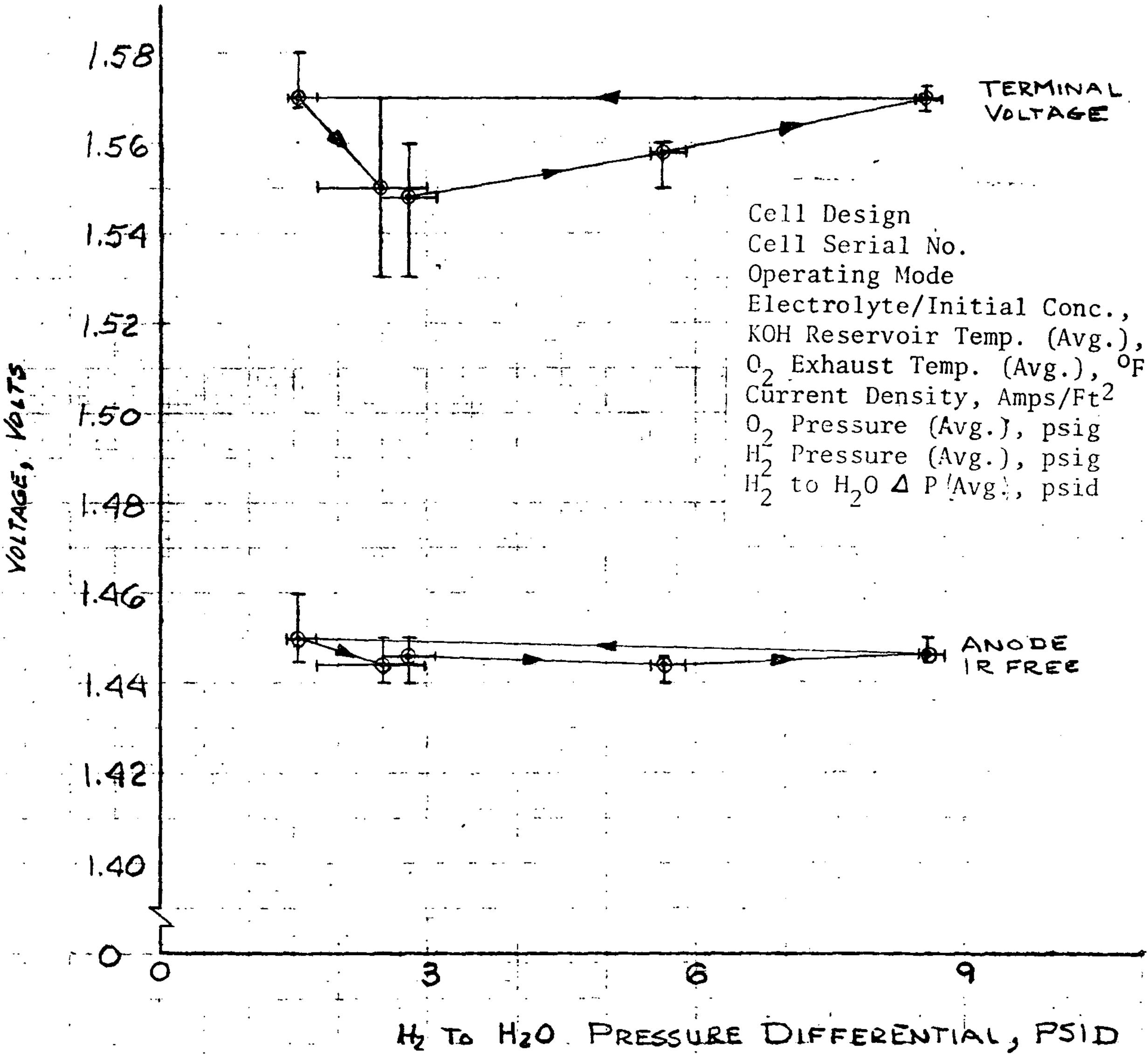


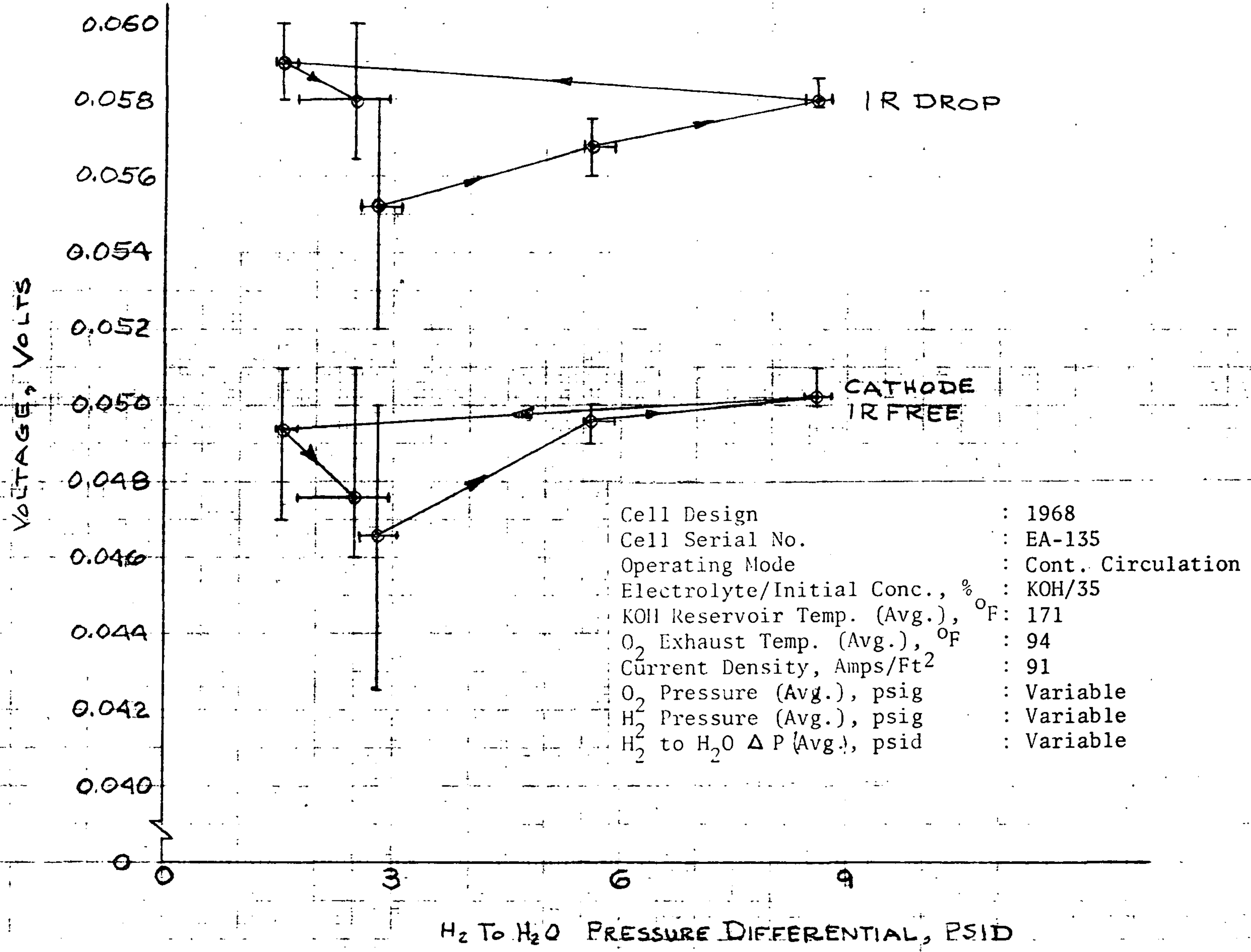
FIGURE 5-27 CATHODE iR FREE AND iR DROP VOLTAGES, VERSUS H_2 TO O_2 PRESSURE DIFFERENTIAL, 1968 DESIGN, EXPERIMENT #2



Cell Design	: 1968
Cell Serial No.	: EA-135
Operating Mode	: Cont. Circulation
Electrolyte/Initial Conc., %	: KOH/35
KOH Reservoir Temp. (Avg.), °F	: 171
O_2 Exhaust Temp. (Avg.), °F	: 94
Current Density, Amps/Ft^2	: 91
O_2 Pressure (Avg.), psig	: Variable
H_2 Pressure (Avg.), psig	: Variable
H_2 to H_2O Δ P (Avg.), psid	: Variable

FIGURE 5-28 TERMINAL AND ANODE iR FREE VOLTAGES VERSUS H_2 TO H_2O PRESSURE DIFFERENTIAL, 1968 DESIGN, EXPERIMENT #3

12-28 DK



Cell Design	1968
Cell Serial No.	EA-135
Operating Mode	Cont. Circulation
Electrolyte/Initial Conc., %	KOH/35
KOH Reservoir Temp. (Avg.), °F	171
O_2 Exhaust Temp. (Avg.), °F	94
Current Density, Amps/Ft^2	91
O_2 Pressure (Avg.), psig	Variable
H_2 Pressure (Avg.), psig	Variable
H_2 to H_2O Δ P (Avg.), psid	Variable

FIGURE 5-29 CATHODE iR FREE AND iR DROP POTENTIALS VERSUS H_2 TO H_2O PRESSURE DIFFERENTIAL, 1968 DESIGN, EXPERIMENT #3

12-29

increased. After a level of 59.8×10^3 N/m^2 differential (8.7 psid) had been reached and maintained for 1 hour the differential was decreased to 10.3×10^3 N/m^2 (1.5 psid) and the cell allowed to operate for an additional 1 hour. As can be seen, very little voltage recovery or any voltage changes were observed in decreasing from 59.8×10^3 to 10.3×10^3 N/m^2 differential (8.7 to 1.5 psid). However, upon operating the cell for an additional 2.5 hours, the cell potentials returned very closely to the levels at which testing was originated.

The least amount of change was observed in the anode iR free voltage with the iR drop showing, on a percent basis, the greatest amount of change with respect to original starting position. Results show that a certain time period is required to regain equilibrium conditions after a high ΔP excursion has been imposed upon the cell. Basically, the iR drop seems to respond sluggishly while terminal and anode free voltages tend to remain constant. Cathode iR free showed almost an immediate improvement in its voltage level as H_2-to-H_2O pressure was decreased to its original levels. The additional 2.5 hours of operation after pressure reduction showed that no permanent damage or permanent blockage of pores had resulted during the overpressure excursion.

5.3.3 1968-Design Cell Disassembly

A 1968 single cell was supplied to be utilized in determining number, shape and dimension of the individual parts that comprise a single cell. Since the cell has to be destroyed in order to identify parts and dimensions, a nonoperative cell (EA-139) was furnished for this purpose. The basic Allis-Chalmers electrolysis cell utilizes solvent bonded polysulfone sheets that are assembled after the parts are dipped into a solvent, presumed to be ethylene dichloride, and then pressed at some elevated temperature level and allowed to set. It was, therefore, impossible to separate the cell into its original parts and a cutting technique was chosen to determine cell part identifications and dimensions. The cell was cut at planes perpendicular to the electrode planes. These cuts were located at strategic areas to obtain sections that would give an indication of cell dimensions and strata.

The single cell was of a typical static vapor feed configuration having a H_2O feed cavity, a H_2 cavity, and an O_2 cavity with the H_2 cavity between the H_2O and O_2 cavities. Porous nickel placque electrodes sandwiched an asbestos cell matrix while perforated polysulfone sheets flanked a teflon membrane and asbestos feed matrix composite, used to separate H_2 gas from the H_2O cavities. The teflon membrane was on the side toward the H_2 compartment. Each of the cavities had two access ports on opposite ends of the cell. Cavities, both H_2O and gases, were typically generated by slotted polysulfone spacers. A heater wire, approximately 1.78 m (70 in.) long, was woven and bonded between two polysulfone sheets and ran adjacent to the H_2O feed cavity. The electrical leads to the electrodes were formed by the actual support screen of the electrode itself, running through the polysulfone. The seal between polysulfone and this nickel screen seemed excellent. The general overall dimensions of the cell were 13.3 x 20.3 cm (5.25 x 8 inches). Cell thickness around the outer edge varied from 0.838 to 0.856 cm (0.330 to 0.337 inches). The center of the cell was at 0.876 cm (0.345 inches) giving the cell a slight bulging appearance. The actual active area for the particular cell assembly was 7.93 x 13.59 cm (3.12 x 5.35 inches) or 107.68 cm^2 (16.69 in^2). This is equivalent to 0.011 m^2 (0.1159 ft^2) or at 11.59 amperes the cell will be exposed to 108 mA/cm^2 (100 A/ft^2). One noteworthy observation was that the cell's anode appeared to be an unplatinized porous nickel placque. The cathode showed a platinum loading. During disassembly of the cell it was noted that both cell and feed matrices were slightly misaligned causing overlapping with the matrix spacer ring that is supposed to frame each matrix. It is unknown what the effect of this misalignment was upon cell performance.

Table 5-4 lists the cell parts identified during its disassembly. Also shown are general part dimensions and other appropriate comments. Figure 5-30 is a cross-section through the cell edge and the fluid cavities. A typical manifold hole is also shown.

TABLE 5-4

CELL EA-139 PARTS IDENTIFICATIONS & DIMENSIONS

Cell Wt.: 329 gms

Cell Size: 0.330 to 0.337 thickness at edge, 0.345 at center
5.25 x 8.00 overall dimension

Cell composed of 19 laminated sections of polysulfone at the edge

* 1	O_2 Cavity Cover Plate 0.029 x 5.25 x 8.00**	
2	O_2 Gas Cavity Spacer 0.021 x 5.25 x 8.00	11 slots 0.17 wide x 5.75 long 10 supports 0.125 wide
3	O_2 Port Spacer (two) each 0.010 x 5.25 x 8.00 3.30 x 5.75 opening	
4	O_2 Manifold Spacer 0.010 x 5.25 x 8.00 3.30 x 5.60 opening	
5	Anode Electrode Porous Nickel Plaque, 25 mesh 0.0115 wire 3.12 x 5.35 active area 0.037 x 3.3 x 5.5 (porous Nickel Plaque) 0.037 x 4.75 x 5.5 (overall dimensions)	
6	Electrode-Matrix Separator Frame 0.010 x 5.25 x 8.00 with 3.12 x 5.35 opening	
7	Matrix, Asbestos 0.028 x 3.75 x 5.96	
8	Matrix Frame 0.021 x 5.25 x 8.00	
9	Electrode-Matrix Separator Frame 0.010 x 5.25 x 8.00 with 3.12 x 5.35 opening	
10	Electrode Porous Nickel Plaque, 25 mesh, 0.0115 wire 3.12 x 5.35 active area 0.037 x 3.3 x 5.5 (Platinized/Porous Nickel) 0.037 x 4.75 x 5.5 (overall dimensions)	

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* See Figure 5-30
** All dimensions in inches

continued-

TABLE 5-4 - Continued

11	H_2 Manifold Spacer 0.010 x 5.75 x 8.00 3.30 x 5.60 opening	
12	H_2 Port Spacer (two) Each 0.010 x 5.25 x 8.00 3.30 x 5.75 opening	
13	H_2 Gas Cavity Spacer 0.021 x 5.25 x 8.00	11 slots 0.17 wide x 5.75 long 10 supports 0.125 wide
14	Perforated Feed-Matrix Support Plate (Upper) 0.010 x 3.50 x 5.75, 400 - 0.027 dia. holes per square inch	
15	Perforated Feed-Matrix Support Plate Frame 0.010 x 5.25 x 8.00	
16	Membrane (Zitex) 0.0035 to 0.005 x 3.50 x 5.75	
17	Matrix, Asbestos 0.028 x 3.75 x 6.00	
18	Matrix Frame 0.021 x 5.25 x 8.00	
19	Perforated Feed-Matrix Support Plate (Lower) 0.020 x 5.25 x 8.00, 400 - 0.027 dia. holes per square inch	
20	Feed Cavity Spacer 0.040 x 5.25 x 8.00	11 slots 0.17 wide x 5.75 long 10 supports 0.125 wide
21	H_2O Manifold/Port Spacer 0.028 x 5.25 x 8.00	
22	H_2O Manifold Spacer/Heater Support Plate 0.028 x 5.25 x 8.00 NOTE: Heater wire woven onto this plate	
23	Heater Cover Plate 0.022 x 5.25 x 8.00	
24	Heater Wire, 0.005 dia. x 70 long, 152 ohm resistance	

CELL EA 139

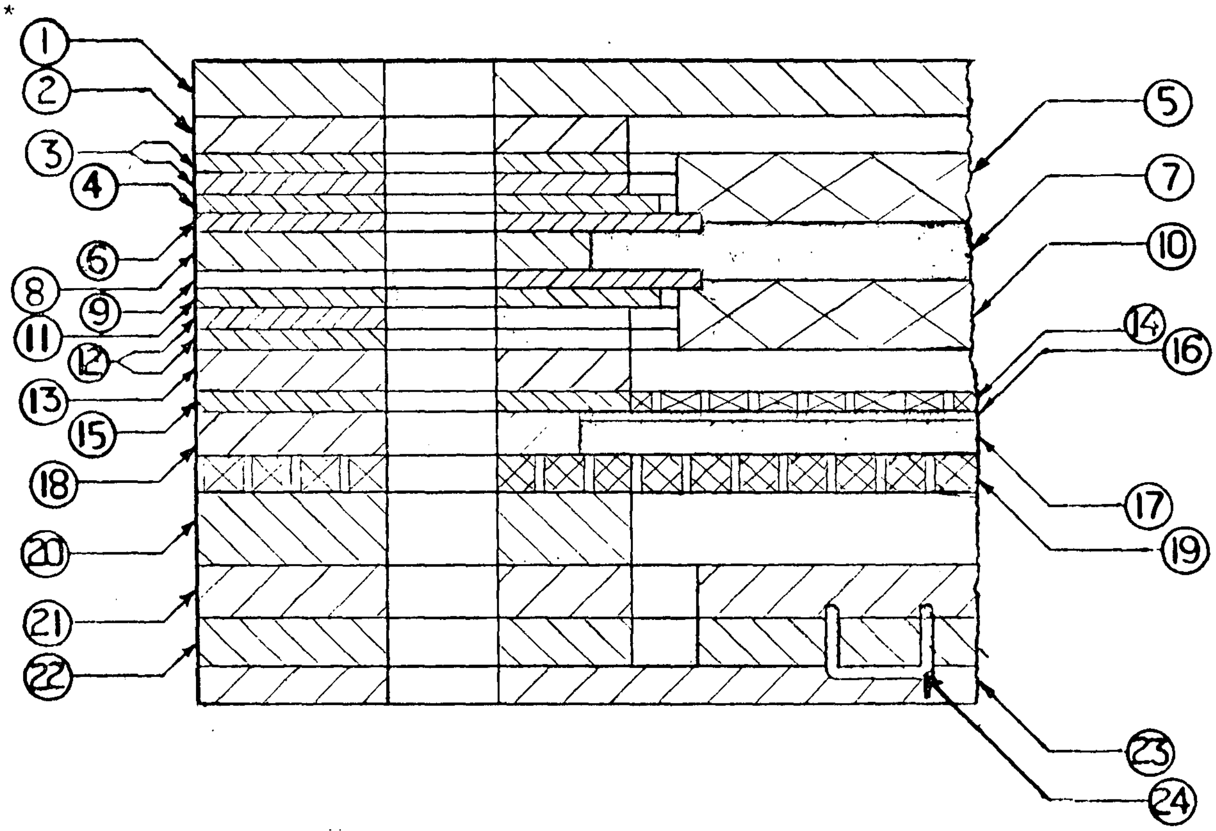


FIGURE 5-30 CROSS-SECTION THROUGH 1968 DESIGN CELL

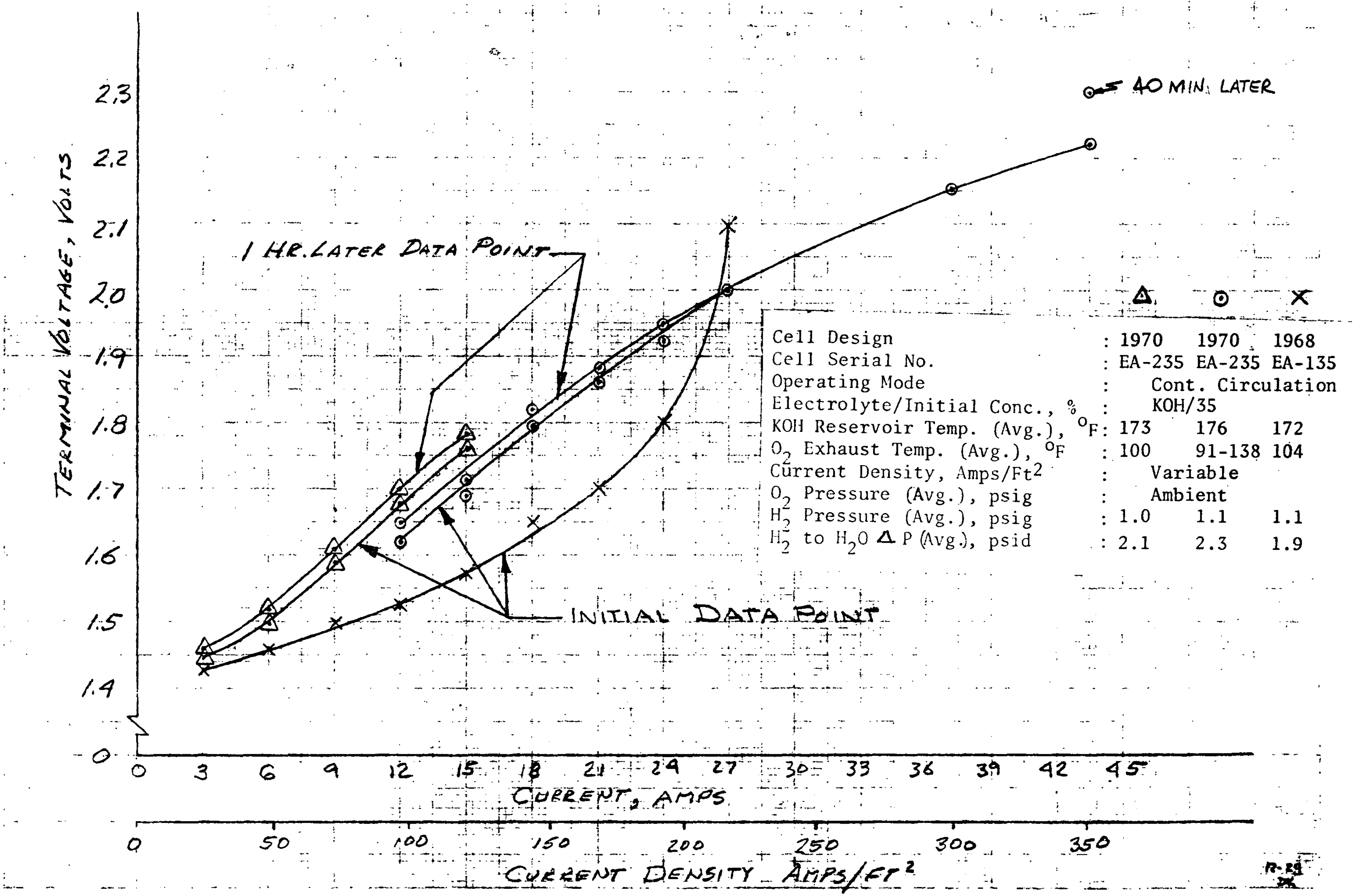
*See Table 5-4

Based on the disassembly experience it can be stated that major repair at the cell level is highly impractical. Under major repair one would consider electrode or matrix replacement or polysulfone part replacement. Only minor repairs in the port and manifold areas or in the o-ring sealing areas would be feasible. Heater tabs which connect the heater wire to external power source were very brittle and susceptible to damage; however, repair of the heater tabs is feasible. Any fault isolation at the cell level would most likely have to be restricted to visual observation of the cell during operation between two plastic and polished end plates. Such a setup could be used to discover and pinpoint locations of crossleaks or internal to external leakage.

5.3.4 1970 Design Cell

Experiments #1 and #4 on the 1970 design cell were conducted similarly to those for the 1968 cell design. Similar pressure and temperature levels and the continuous KOH circulating mode were again employed. One difference in the data obtained is that no half cell potentials were possible since the 1970 cell was not physically altered. Also Experiment #1 was conducted during one working day with Experiment #4 being conducted the following working day.

Figure 5-31 shows the terminal voltage versus cell current and current density for Experiments #1 and #4 for a 1970 design cell. Experiment #1 data is indicated by triangles and Experiment #4 data is indicated by circles. Results of the 1968 design cell are also shown, by crosses, for comparison purposes. In Experiment #1 current was varied from 3 through 15 amperes. The data resulted in a typically shaped curve expected from electrolysis cells operating within the range of tolerance to current level. The slope, however, is steeper than that of the 1968 design cell being 30 mv per ampere as compared to 12.5 mv per ampere. The results of Experiment #4 (voltages above 1.7 volts) shows an excellent response and tolerance of the 1970 design at increased current densities. The slope is decreasing as



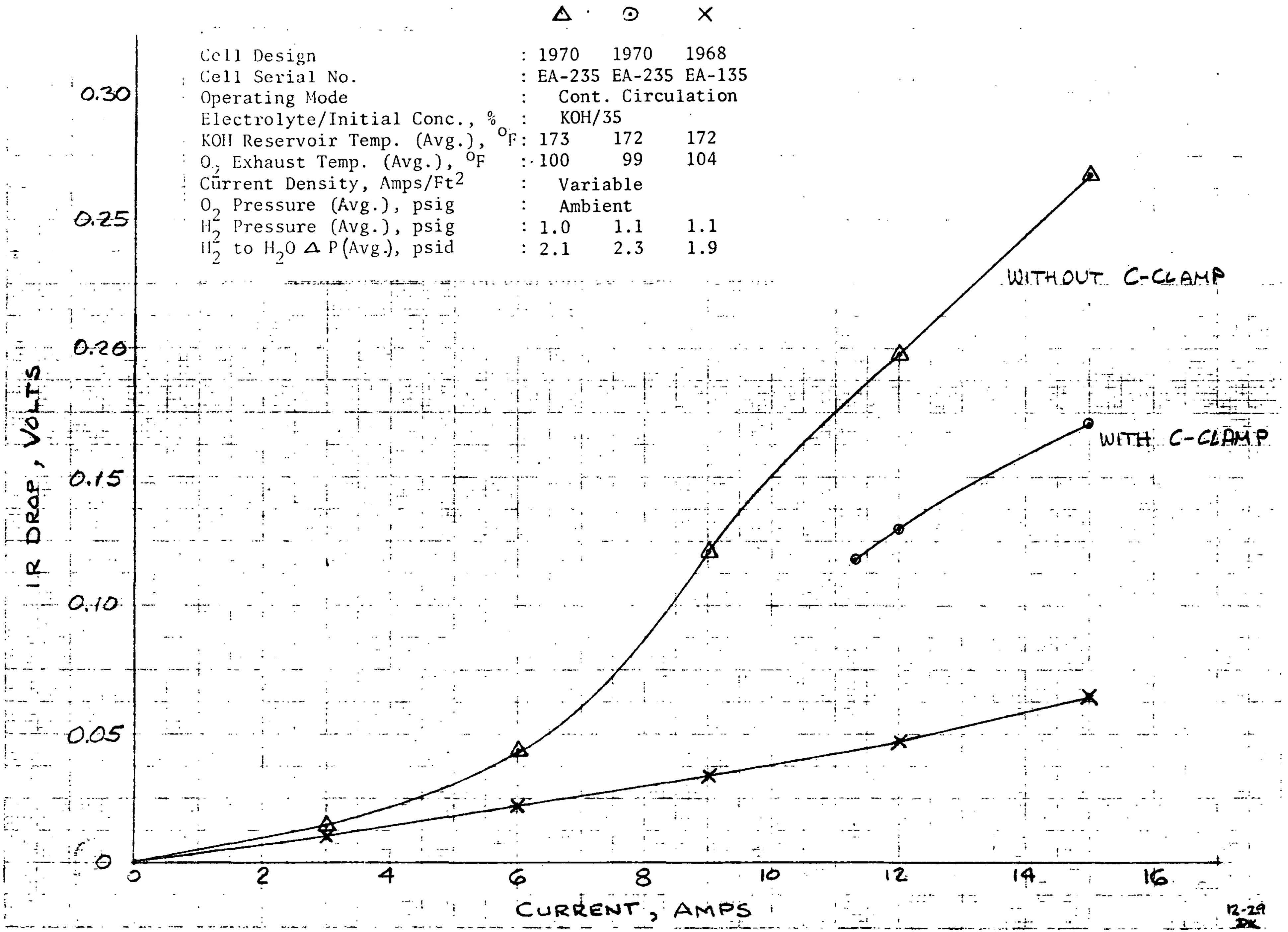
		△	⊙	×
Cell Design	:	1970	1970	1968
Cell Serial No.	:	EA-235	EA-235	EA-135
Operating Mode	:	Cont. Circulation		
Electrolyte/Initial Conc., %	:	KOH/35		
KOH Reservoir Temp. (Avg.), °F	:	173	176	172
O_2 Exhaust Temp. (Avg.), °F	:	100	91-138	104
Current Density, Amps/Ft^2	:	Variable		
O_2 Pressure (Avg.), psig	:	Ambient		
H_2 Pressure (Avg.), psig	:	1.0	1.1	1.1
H_2 to H_2O Δ P (Avg.), psid	:	2.1	2.3	1.9

FIGURE 5-31 TERMINAL VOLTAGE VERSUS CURRENT, 1970 DESIGN, EXPERIMENTS #1 AND #4

current increases. The value of the slope above 27 amperes is 13.4 mv per ampere, very similar to the inital slope of the 1968 design. Only at 377 mA/cm^2 (350 A/ft^2) (43.4 amps) did a data spread occur between the initial voltage level and the voltage level 1 hour later.

In the area between 12 through 15 amperes, a decided decrease in the voltage levels for Experiment #4 are noted over those from Experiment #1. This was achieved by applying a compression force in the center of the cell endplates via a C-clamp. A literature survey had shown that the 1970 versions needed additional compression in the center of the cell. Two 0.013 cm (0.005 in.) polysulfone shims, supplied with the cell, had been used in assembling the 1970 design, one on each side of the cell when sandwiched between the plastic endplates. The cell was not measured to determine how much shim material should be used. To verify its susceptability to a compression force, a C-clamp was applied. The resulting decrease in overall cell voltage is shown between the ranges of 12-15 amperes.

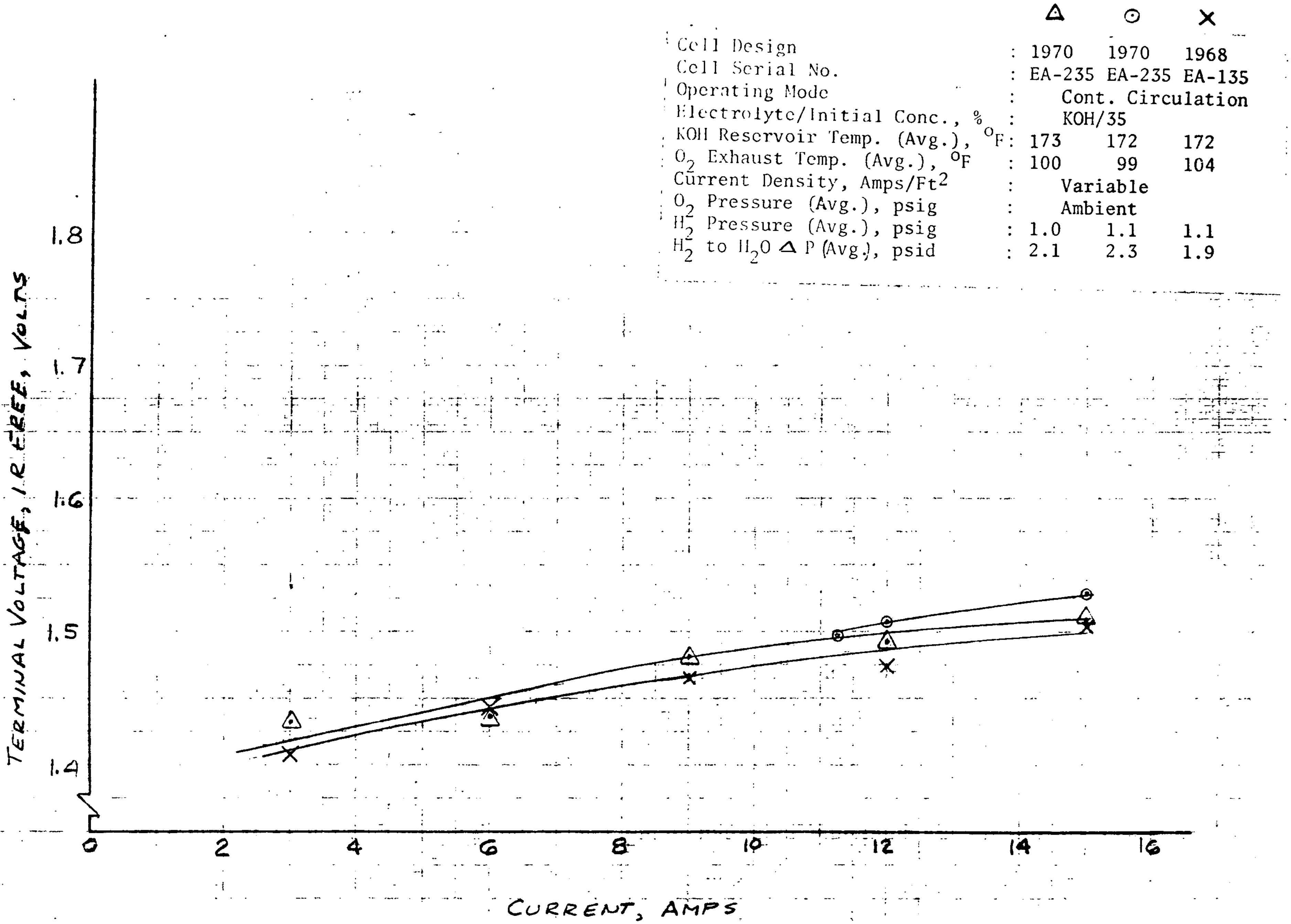
Figure 5-32 shows the iR drops versus current for the 1970 designs, Experiment #1 and #4, and also shows the iR drop of the 1968 design, indicated for comparison purposes. As can be seen from the figure, the iR slopes of the 1970 design with and without the additional C-clamp force are substantially higher than the slope of the iR drop for the 1968 design over the same current range. The quantitative relationships of the slopes are 25 mv per ampere for the 1970 design, Experiment #1, without C-clamp and above 6 amperes and 7.5 mv below 6 amperes, 15 mv per ampere for Experiment #4, 1970 cell design with C-clamp, and a slope of 4.3 mv per ampere for Experiment #1 of the 1968 design. The 1968 design was never operated with a C-clamp. Figure 5-33 shows the iR free terminal voltages for the three cases discussed in Figure 5-32, i.e., Experiment #1 - 1970 design, Experiment #4 - 1970 design, and Experiment #1 - 1968 design. As can be seen, the iR free terminal voltages for all three cases are identical within the accuracy of the data obtained. The difference observed, therefore, in



		△	⊙	×
Cell Design	:	1970	1970	1968
Cell Serial No.	:	EA-235	EA-235	EA-135
Operating Mode	:	Cont. Circulation		
Electrolyte/Initial Conc., %	:	KOH/35		
KOH Reservoir Temp. (Avg.), °F	:	173	172	172
O_2 Exhaust Temp. (Avg.), °F	:	100	99	104
Current Density, Amps/Ft^2	:	Variable		
O_2 Pressure (Avg.), psig	:	Ambient		
H_2 Pressure (Avg.), psig	:	1.0	1.1	1.1
H_2 to H_2O Δ P (Avg.), psid	:	2.1	2.3	1.9

12-29
DK

FIGURE 5-32 IR DROP VERSUS CURRENT, 1968 AND 1970 DESIGN



		Δ	⊙	×
Cell Design	:	1970	1970	1968
Cell Serial No.	:	EA-235	EA-235	EA-135
Operating Mode	:	Cont. Circulation		
Electrolyte/Initial Conc., %	:	KOH/35		
KOH Reservoir Temp. (Avg.), °F	:	173	172	172
O_2 Exhaust Temp. (Avg.), °F	:	100	99	104
Current Density, Amps/Ft^2	:	Variable		
O_2 Pressure (Avg.), psig	:	Ambient		
H_2 Pressure (Avg.), psig	:	1.0	1.1	1.1
H_2 to H_2O Δ P (Avg.), psid	:	2.1	2.3	1.9

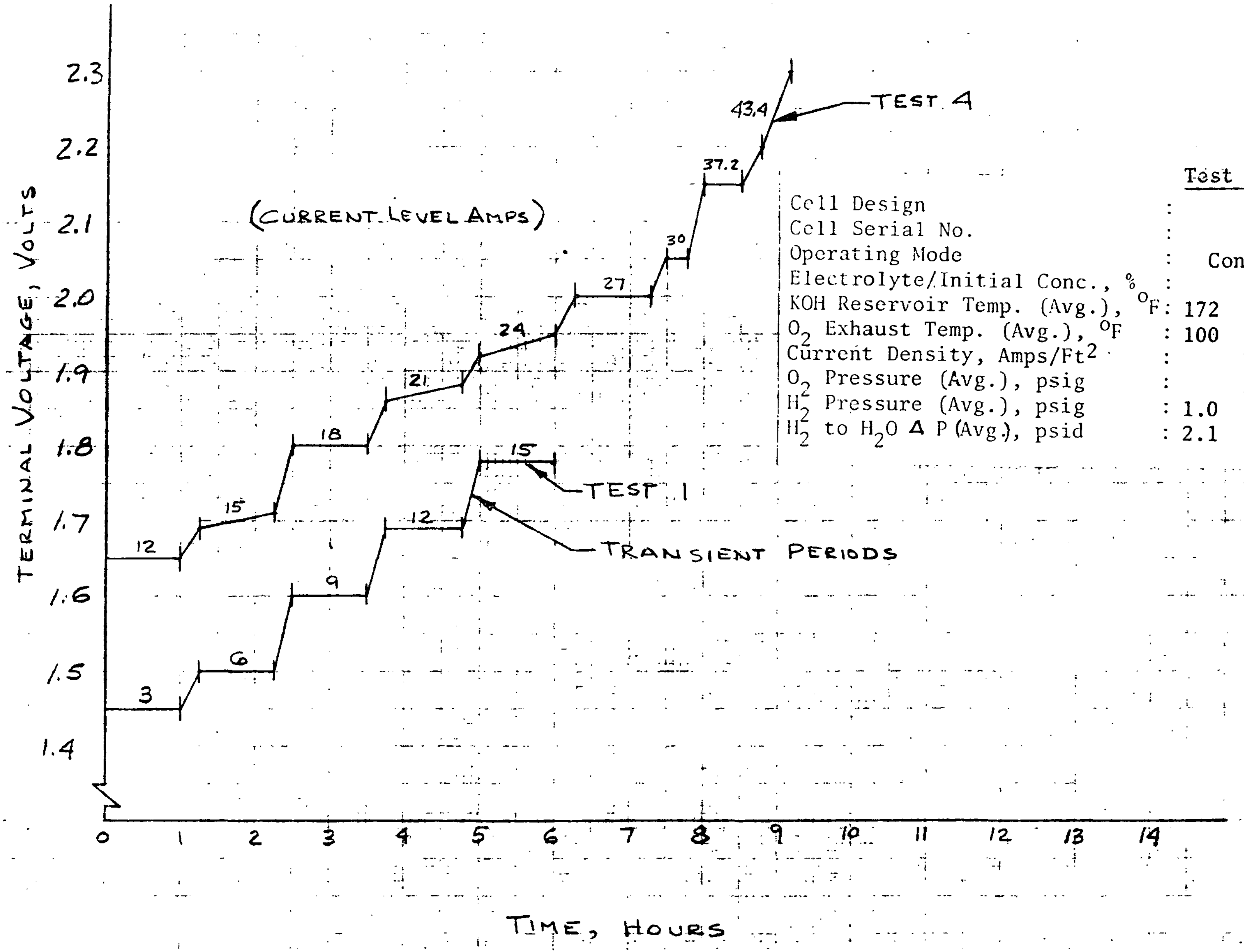
FIGURE 5-33 IR FREE TERMINAL VOLTAGE VERSUS CURRENT, 1968 & 1970 DESIGN

12-29
DB

Figure 5-31 between voltage slopes for the three conditions was strictly due to internal resistance differences. The addition of a C-clamp in Experiment #4 for the 1970 design strictly affected internal resistance.

Figure 5-34 shows terminal cell voltage versus time for various current levels of Experiments #1 and #4 of the 1970 cell design. Compared to Figure 5-23, a similar curve for the 1968 design, the voltage levels at each current density remain constant with time at higher currents for the 1970 design as compared for the 1968 design.

The 1970 design cell was subjected to a H_2-to-O_2 pressure differential test over a range of -41.3×10^3 to $+ 41.3 \times 10^3$ N/m^2 differential (-6 to +6 psid). Both terminal and iR drop voltages were recorded for a sequence of H_2-to-O_2 pressure differentials of $+ 6.89 \times 10^3$, -13.8×10^3, -27.6×10^3, -41.3×10^3, $+6.89 \times 10^3$, $+13.8 \times 10^3$, $+27.6 \times 10^3$, $+41.3 \times 10^3$, and $+6.89 \times 10^3$ N/m^2 differential (+ 1, -2, -4, -6, +1, +2, +4, +6, and +1 psid). Each pressure differential level was maintained for a 30-minute period with data taken at 10 minute intervals. Figure 5-35 shows the result of the test. Ranges of voltage levels observed while the data was taken are indicated with the average values used to plot the curves shown. The data indicates that decreasing the H_2-to-O_2 pressure differential typically increases terminal voltage and iR drop. Returning in an increasing direction of H_2-to-O_2 pressure differential typically results in a decrease in terminal voltage and iR drop. The horizontal line from -41.3×10^3 to $+41.3 \times 10^3$ N/m^2 differential (-6 to +6 psid) indicates that a time lag is involved in restoring close to original voltage levels after a ΔP excursion. The one-half hour duration at each data point was not sufficient to restore voltage levels to their prior values. The 1968 design showed a similar trend in voltage, however, the absolute values for the 1968 design were lower than for the 1970 design. Based on the discussion above, the main reason for the higher absolute levels is the higher internal resistance observed for the 1970 design. The changes with ΔP in terminal voltage and in iR drop voltage are also higher in the 1970 design as compared to the



	Test 1	Test 4
Cell Design	1970	
Cell Serial No.	EA-235	
Operating Mode	Cont. Circulation	
Electrolyte/Initial Conc., %	KOH/35	
KOH Reservoir Temp. (Avg.), °F	172	176
O_2 Exhaust Temp. (Avg.), °F	100	91-138
Current Density, Amps/Ft^2	Variable	
O_2 Pressure (Avg.), psig	Ambient	
H_2 Pressure (Avg.), psig	1.0	1.1
H_2 to H_2O Δ P (Avg.), psid	2.1	2.3

FIGURE 5-34 TERMINAL VOLTAGE VERSUS TIME, 1970 DESIGN, EXPERIMENTS #1 AND #4

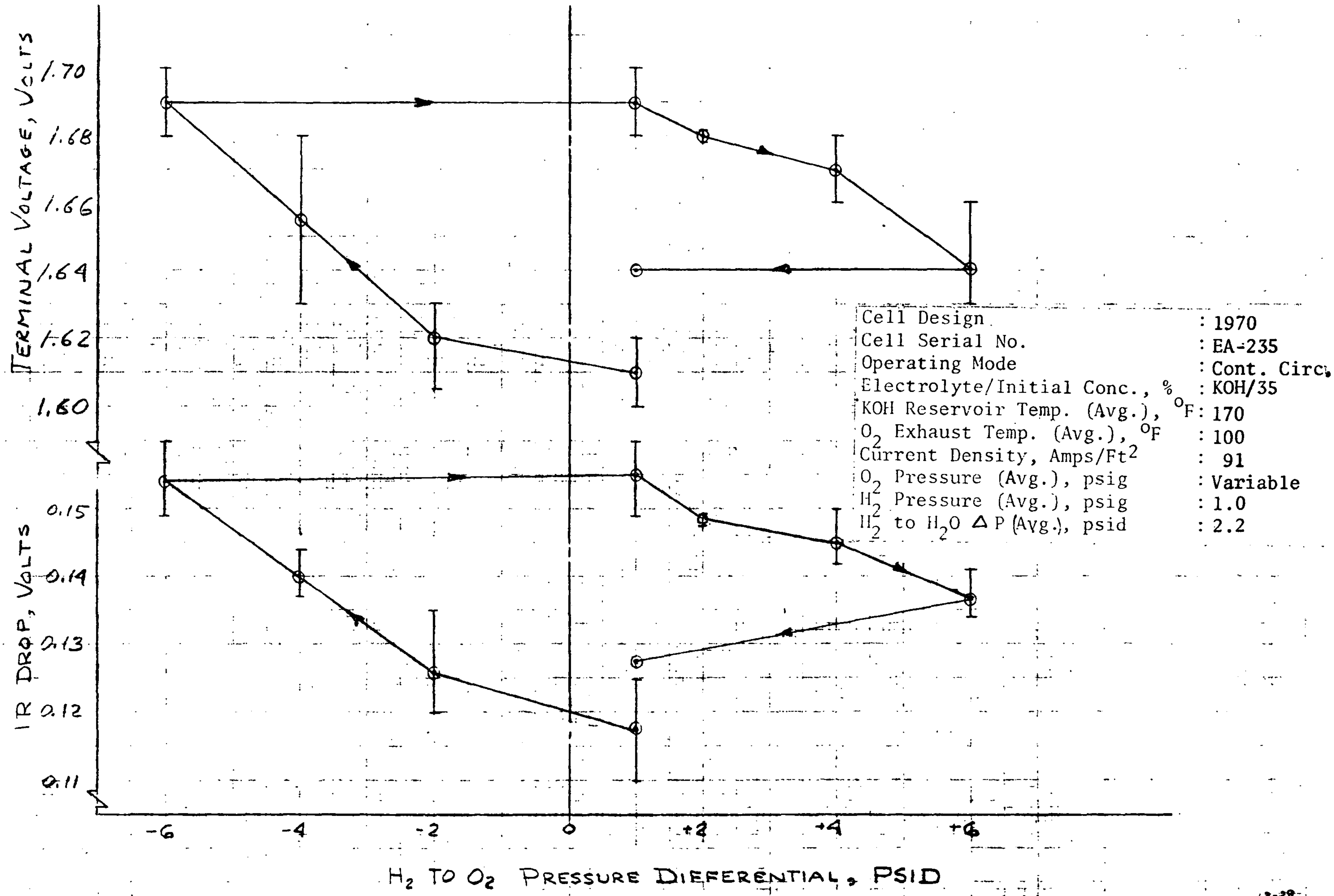


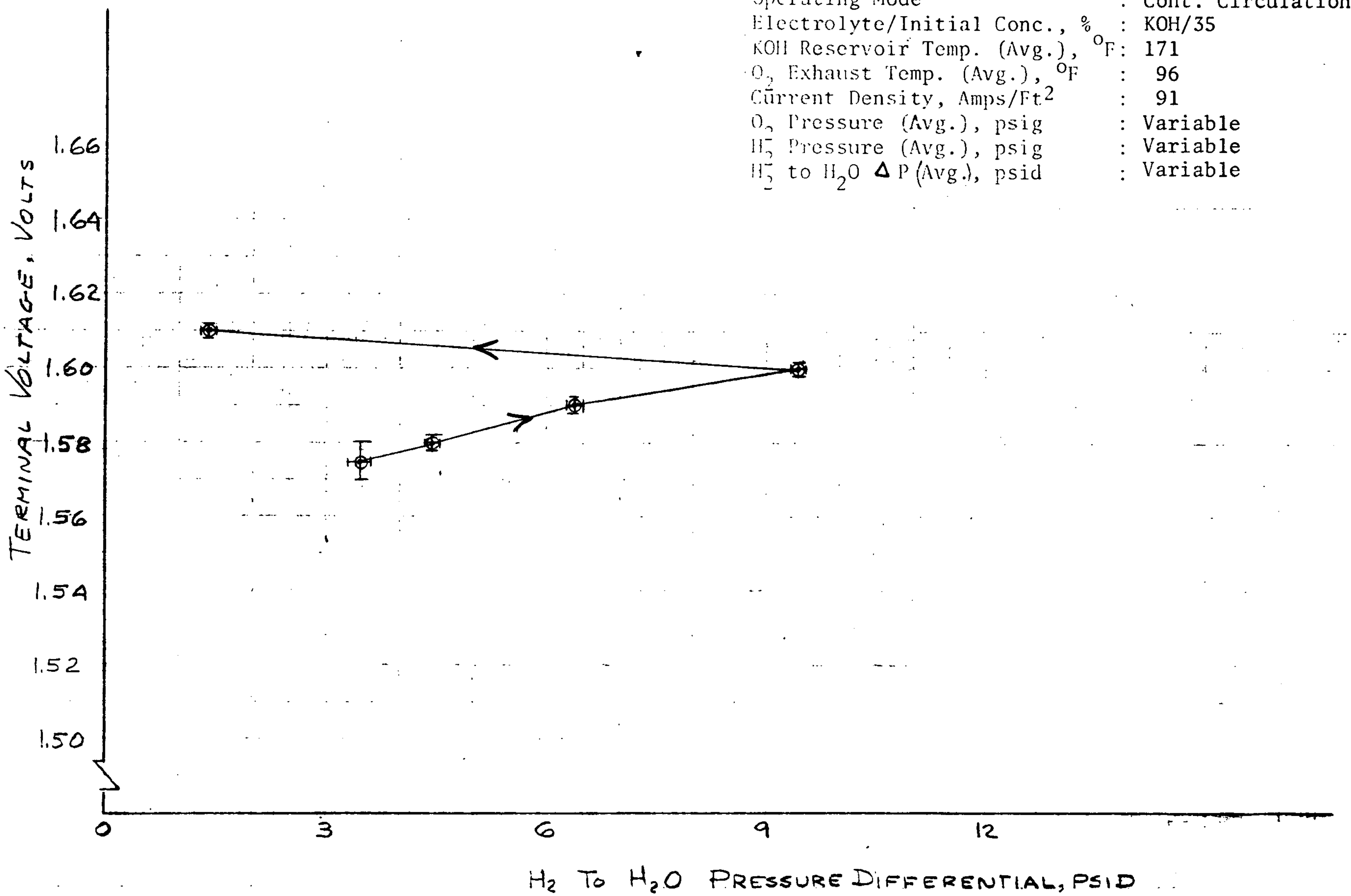
FIGURE 5-35 TERMINAL VOLTAGE AND iR DROP VERSUS H_2 TO O_2 PRESSURE DIFFERENTIAL, 1970 DESIGN, EXPERIMENT #2

12-28
RK

1968 design. The 1970 design had an 80 mv change in terminal voltage compared to 25 mv in the 1968 design and a 37 mv change in iR drop compared to a 2 mv change in the 1968 design for the ΔP range of ± 41.3 x 10^3 N/m^2 differential (± 6 psid). The results show that the 1970 design appears to be more susceptible to ΔP effects.

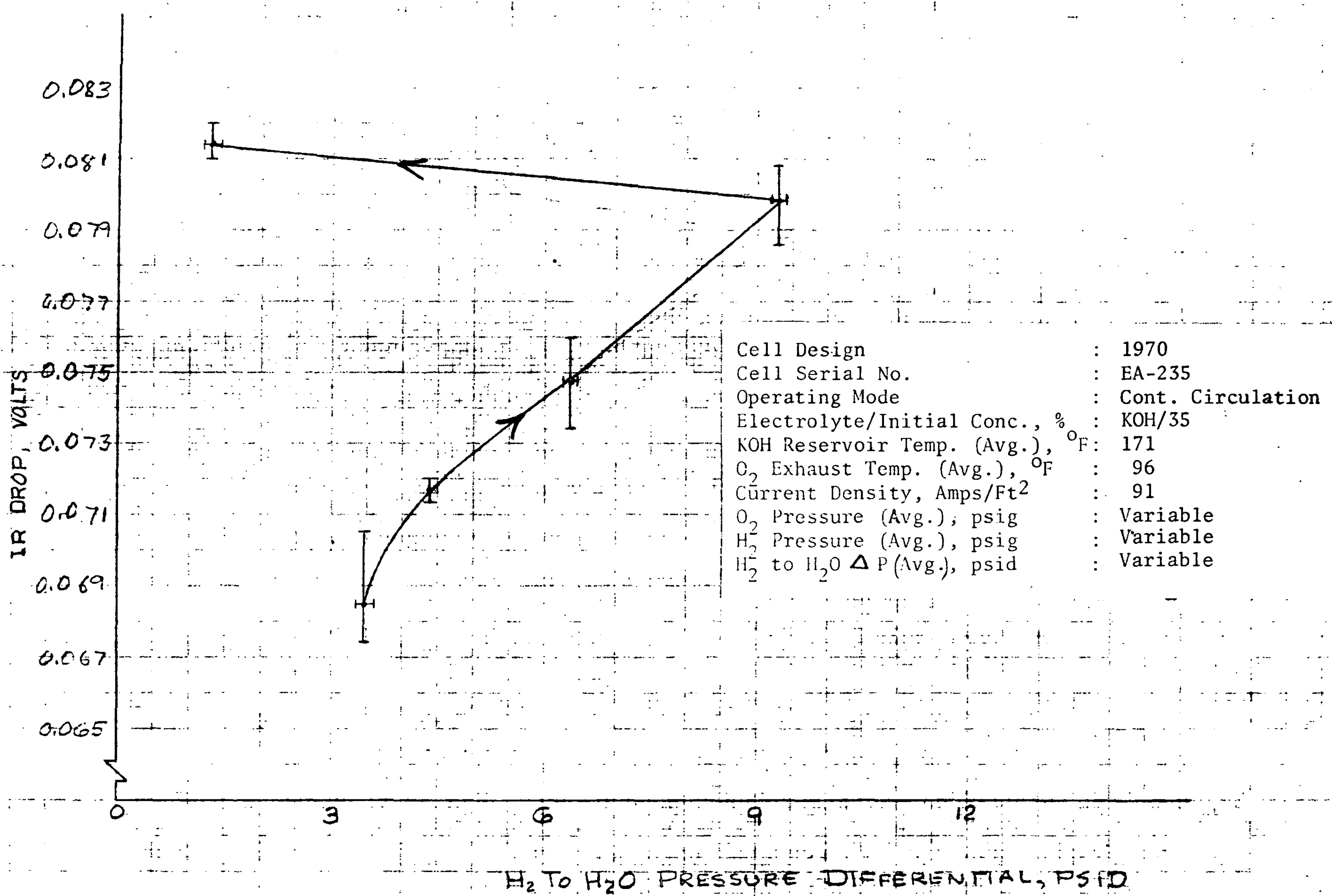
Experiment #3 for the 1970 cell was conducted similarly to that of the 1968 cell. The H_2-to-H_2O pressure was increased while maintaining the H_2-to-O_2 pressure differential constant. All other parameters were maintained at levels similar to those in the 1968 ΔP test. Specific values for the operating parameters are indicated on Figures 5-36 and 5-37. Data was taken at 5 values of H_2-to-H_2O ΔP; 24.1 x 10^3, 30.3 x 10^3, 44.1 x 10^3, 64.7 x 10^3, and 9.64 x 10^3 N/m^2 differential (3.5, 4.4, 6.4, 9.4, and 1.4 psid). The system was operated at each pressure level for 1 hour with data taken every 15 minutes. Figures 5-36 and 5-37 show the results of the H_2-to-H_2O ΔP tests for the 1970 design. Again, ranges of observed parameters during the 1 hour at any one operating condition are indicated. The average values are used to plot the curves. The general shape of the curve indicates that increasing H_2-to-H_2O ΔP causes a rise in terminal voltage and iR drop. This is similar to what was observed with the 1968 cell. Reducing the H_2-to-H_2O pressure differential to 9.64 x 10^3 N/m^2 (1.4 psid) from 64.7 x 10^3 N/m^2 (9.4 psid) showed negligible changes in terminal voltage and iR drop. This was still observed after 2.5 hours of operation at the lower ΔP level.

The absolute levels of iR drop and terminal voltage were higher for the 1970 cells as compared to the 1968 cells. Also, a change in voltage fluctuation in the 1968 cell was from 1.55 to 1.57 volts, or a 20 mv change, in the terminal voltage and 0.055 to 0.059 volts, or a 4 mv change, in iR drop. The equivalent changes for the 1970 cell terminal voltages were from 1.575 to 1.61 or a 35 mv change. For the iR drop the voltages varied from 0.0685 to 0.0815 or a 13 mv change. Experiment #3 conducted on the two cell types indicated that the voltage levels of the 1970 design cells are affected to a greater degree by H_2-to-H_2O ΔP than those of the 1968 cell design.



Cell Design : 1970
Cell Serial No. : EA-235
Operating Mode : Cont. Circulation
Electrolyte/Initial Conc., % : KOH/35
KOH Reservoir Temp. (Avg.), °F : 171
O_2 Exhaust Temp. (Avg.), °F : 96
Current Density, Amps/Ft^2 : 91
O_2 Pressure (Avg.), psig : Variable
H_2 Pressure (Avg.), psig : Variable
H_2 to H_2O Δ P (Avg.), psid : Variable

FIGURE 5-36 TERMINAL VOLTAGE VERSUS H_2 TO H_2O PRESSURE DIFFERENTIAL,
1970 DESIGN, EXPERIMENT #3



Cell Design	:	1970
Cell Serial No.	:	EA-235
Operating Mode	:	Cont. Circulation
Electrolyte/Initial Conc., %	:	KOH/35
KOH Reservoir Temp. (Avg.), °F	:	171
O_2 Exhaust Temp. (Avg.), °F	:	96
Current Density, Amps/Ft^2	:	91
O_2 Pressure (Avg.), psig	:	Variable
H_2 Pressure (Avg.), psig	:	Variable
H_2 to H_2O Δ P (Avg.), psid	:	Variable

FIGURE 5-37 IR DROP VERSUS H_2 TO H_2O PRESSURE DIFFERENTIAL, 1970 DESIGN, EXPERIMENT #3

5.4 Review of Past Performance of SVFU Modules By Life Systems, Inc.

Part of the effort to be performed by LSI was to review past performance of the Allis-Chalmers SVFU. The purpose of this review was to: inform LSI personnel of the detailed characteristics of the AC cell and modules; review the causes of failures that had been experienced in previous test programs, to show agreement, or disagreement with justifications, for these conclusions; and identify and detect any possible characteristics and cause of failures that would assist MDAC in performance of the 182-day test. Four distinct sets of test data were available for the review, these included:

a) A 100-hour acceptance test conducted at MDAC in December, 1969.

b) A 90-day test started in June, 1970 at MDAC.

c) Refurbishment tests conducted at the manufacturers (AC) facility during November 1970

d) A 48-hour acceptance test conducted at the manufacturers (AC) facility during February 1971.

The first two tests were conducted on the total self-contained unit as designed for the 90-day test, while the last two tests were conducted at the module and/or cell level.

This section presents the results and conclusions obtained from reviewing the literature furnished by MDAC describing the tests a) through d) mentioned above. Also, a copy of the manufacturer's operation and maintenance manual was reviewed in conjunction with the test reports to serve as a reference to the systems operation and design.

5.4.1 100-Hour Acceptance Test - December 1969

This test was conducted after receipt of the SVFU by MDAC to verify system operability prior to installation of the unit into the 90-day manned test chamber. At 1615 hours of the afternoon of December 15, 1969, the 100-hour acceptance test of the WES for the 90-day test was started at the Huntington Beach laboratory of MDAC. The first data point taken at 1700 hours revealed that an immediate problem existed with module 2. At that particular time cell #15 of module #2 showed a voltage of 0.1 volts. Thermocouple #8, located near cell #15, recorded 350°K (170°F), the highest of the 12 thermocouples for the three operating modules. Module current for #2 at that particular time was 15.1 amps.

Typically, an indication of extremely low cell voltage results from loose sensor wiring for the cell voltage, a crossover of large magnitude within a particular cell (for a reading below 1.4 volts/cell) or an external electrical short between electrode leads. Severe crossover within a cell or cells can also be detected by comparing the actual gas flow rates compared to those theoretically resulting based on the current flowing. During the particular time in question (cell #15 $\sim$ 0) 0.13 m^3/hr of hydrogen were recorded. Based on the currents flowing, a total of 0.166 m^3/hr of hydrogen should have been produced. The resulting efficiency is 78%, far below that which is to be expected from a unit of this type. It can therefore be concluded that a severe crossover was occurring within module #2. As time went on, cell #15 maintained its 0.1 volt reading while the temperature located near cell #15 continued to rise to a level near 366°K (200°F).

Eventually dryout of the feed matrix of cell #15 must have resulted due to the excessive heat generated causing gases to seep into the feed water compartments of module #2 which caused other cells to rise in cell voltage. This was shown to occur approximately 4 hours after startup when cells #6 and #11 started to show rises in their cell voltages, eventually reaching 2+ volts per cell. The temperature of thermocouple #8 was 366°K (199°F) at that particular point. Seven hours after startup, module #2 was secured and replaced with module #5. The efficiency throughout this test, based on hydrogen production rate, varied between 77 and 88%, showing that continuous crossover or a fuel cell reaction occurred.

These results showed that the system did not possess adequate monitoring and fault detection to prevent dangerous conditions, such as a crossover, to exist. Also, the Operations and Maintenance Manual did not call out low cell voltage (< 1.4 volts) as an emergency condition requiring system shutdown. A voltage check with an external voltmeter at the tabs of cell #15 on module #2 would have verified crossover and eliminated the possibility of the cause being faulty wiring to the meter on the front panel. Initial cause of the crossover could have been an electrical short between the two electrode current tabs protruding out of cell #15. If the two tabs were shorted together, cell #15 would act as a fuel cell with a high current due to the low resistance shorting load.

Aside from a required module flush of module #1 on the second day of operation, the performances of the three modules of the WES appeared acceptable from an individual cell and module point of view. Gas production efficiencies during the remainder of the test varied between 97 to 100% and are considered within the accuracy of typical instrumentation used to measure the parameters. Operation at elevated current levels (15 to 16 amps or approximately 140 mA/cm^2 (130 A/ft^2) showed that the passive or evaporative cooling method is far from adequate in controlling module temperatures for varying production rates and/or environmental conditions, since during this testing temperatures, at times, exceeded 367°K (200°F).

Review of the test data also showed that during the initial startup the hydrogen pressure averaged approximately 62.0×10^3 N/m^2 differential (9 psid) above the water pressure, more than the allowable pressure differentials stated by the manufacturer. This pressure differential could have hastened problems in module #2 and caused water transport problems resulting in crossover.

5.4.2 90-Day Manned Testing - June - July, 1970

A general review of the available data showed that a large number of failures were attributable to peripheral equipment which is herein defined as all equipment other than the modules. Failure in the peripheral equipment included electronic failures, regulator failures, and pump failures.

The most critical failures of the system consisted of its inadequacy to produce the required amount of oxygen; i.e., maintain a desired module current while maintaining module voltages and temperatures within prescribed limits.

The primary cause of these short-term failures can be traced to the method of water addition used in the system design. The system schematic showed that water was added to the liquid loop upstream of the liquid-gas separator, hence consumption of water within the electrolysis modules by vapor transfer to the electrolysis site caused potassium hydroxide solution to be drawn into the module rather than pure water to make up for the water which was electrolyzed. The mode of operation results in a large KOH concentration buildup in the feed cavities since the volume between the modules and the point of water addition is in excess of several hundred cc's of liquid. This is sufficient to cause crystallization of KOH salt within the feed cavities before makeup water would reach the feed cavities. Without frequent circulation, the system is incapable of operating successfully at normal design for any length of time. (See Section 5.7.4.1). Circulating frequencies of one hour are considered maximum to obtain reasonable module performance. The system would be capable, however, of continuous operation if the liquid were to be circulated continuously through the feed cavities and hence maintain the concentration in the feed compartment constant.

Again, in reviewing the 90-day test data, it can be seen that, as in the 100-hour acceptance test, one of the cells of the WES registered 0 volts at the beginning of the test. This dangerous situation again went uncorrected due to lack of proper instructions or built-in safety devices. The cell was externally shorted. The result was recombination of hydrogen and oxygen with excessive heat generation and cell dry-out. The 90-day test data did not give any indication of hydrogen or oxygen flow rates. The magnitude of the crossover, or the amount of gases consumed can not, therefore, be traced. That recombination took place is evident by the high temperature readings that were obtained on June 13, 1970 during the 90-day test when thermocouples #10 and #11 exceeded 367°K (200°F) within less than 1 day after startup. The cells of module 3 causing this excessive heat-up were cells #3, which showed 0.1 volt, and cell #4 which showed an excess of 2 volts. Cell #3 which was externally shorted out, showed 0 volts at system startup.

This dangerous condition was allowed to exist and was worsened on June 14, 1970 at 1240 hours, when cell #4, module #3, was deliberately shorted out as approved by the AC representative. This definitely caused fuel-celling to occur in cell #4. The excessive heat generated by the recombination was partially removed by frequent circulations of the fluid within the water cavities. The intent, at that time, however, was to maintain cell voltages through gas purging, not to remove heat. Due to that fact, the cell temperatures, as recorded, are only near 367°K (200°F). However, high currents did flow through the external shorting causing gas combination, reduction in gas production, and high heat loads with resulting dry-out of other cells within module #3.

By the third day of the 90-day test, modules #1 and #2 also showed high cell voltages, again, primarily caused by the inability of the unit to operate with the required 2 hour circulation intervals without high concentration build-up in the feed cavities. During the testing excessive hydrogen-to-water pressure differentials were observed. The cause of these high ΔP's could not be determined from the data available. If such ΔP's existed they could cause further module performance degradation due to possible crossover of hydrogen gas into the feed water cavities. If the water transport matrices were in a stage of being dried out due to high concentrations and high heat loads, the ΔP increase over that of the design level would hasten module failure.

Upon restart of the modules on the 18th day of the 90-day test, reasonable performance with the WES was achieved which can be traced to the decision made to purge one module at a time for 15 minutes of each hour. This change in operating mode eliminated the short-term shutdowns caused by high concentration buildups within the feed compartments since the high frequency of circulation was not necessarily required to eliminate gases accumulating in the water cavities. Data on gas purging was not available. Since no mention was made in the test data on quantities of gases purged it is assumed that smaller amounts of gases were accumulating.

It is not known if the proper electrical grounding precautions were taken in designing of the AC unit. These grounding precautions are such that all plumbing hardware in contact with the liquid KOH should be electrically floating rather than being grounded. This minimizes gas generation due to stray electrolysis.

System operation went relatively smoothly through day 19 until again a decision was made to electrically short out cells #9 and #11 on module #3. The data shows the excessive heat generated caused temperatures to read up to 411 °K (280°F) (thermocouple location #11 near the shorted cells). The accompanying dry-out of adjacent cells was seen by the initial increases in voltages above 2 and by cells decreasing to voltages below 1.4, indicating that the crossover had occurred in the latter cells. Cell #10 was of this type with a reading of 1.37 volts. The results forced replacement of module #3 with module #5.

The new module in position #3, or module #5, showed 0 voltages on the data sheet for cells #3 and #4. These cell voltages were zero due to external electrical shorts. In any case, the module life is very short when operating with cells in a shorted condition. It can be seen that the module in position #3 was inoperable within 10 hours after its startup. System shutdown finally occurred on day 20 and the WES was not restarted for the duration of the 90-day test.

5.4.3 Refurbishment Tests - November, 1970

At the conclusion of the 90-day manned chamber test the five modules of the AC electrolysis system were shipped to AC for refurbishment testing. The tests basically consisted of visual inspections, torque checking, external and crossleak checking, operation of the modules with continuous circulation of the fluid through the cell O_2 and H_2O compartments, cell resistance measurements and operation for periods of 2 to 6 hours duration. Based on the tests performed it can be concluded that KOH leakage to the exterior was caused in part by a relaxation of bolt torques, and/or cracking, melting and general structural damage to the polysulfone of the individual cells caused by crossovers with excessive temperatures. The test data shows that all five modules suffered from interior to exterior leaks and/or crossleaks. Especially severe leaks were discovered in modules #3 and #5.

Severe structural cell damage was observed in module #3 from cells #2 through #6. This, without doubt is traceable to the operation with cell #4 being deliberately shorted. Similarly, cells #9 and #11 had been shorted during the 90-day testing in module #5. Module #5 showed excessive crossleaks and interior to exterior leaks. Again, it is believed that this can be traced to the deliberate shorting of these cells.

The performance data obtained from the modules during circulation of electrolyte through both the water and oxygen cavity showed that the electrical performance (cell voltage) obtainable with this type of module is excellent for the current densities tested. For example, cells average 1.50 volts near 108 mA/cm^2 (100 A/ft^2) and 344°K (160°F). It can therefore be stated that the electrode and cell matrix structure is excellent from a performance point of view provided that proper operating conditions and concepts are employed. The data showed that the modules are capable of operation with continuous circulation.

The static vapor feed mode testing conducted during the refurbishment tests referred to circulation of electrolyte through the feed compartments only, with static water addition to a point in the circulating loop.

The refurbishment test data also showed that while crossleaks in a module may exist, rewetting of the asbestos matrices with electrolyte or water will eliminate some of these leaks. It should be noted, however, that even though the leak may be fixed, the particular matrix may retain a permanent weak spot.

5.4.4 48-Hour Acceptance Test - February, 1971

The data available on the 48-hour acceptance test conducted at the manufacturer's facility shows that five modules plus one spare were reassembled utilizing those cells that were acceptalbe from the original modules plus a variety of spare cells to give six 15-cell modules. The data shows that the grouping of the cells was accomplished based on flow rate versus pressure drop data through the water cavities. Cells were grouped within modules having nearly equal pressure drops. In this manner, equal flow distribution during circulating mode of operation is enhanced.

Each module underwent an operating mode in which electrolyte was circulated through both the oxygen and water cavities, followed by operation with electrolyte continually circulated through the water feed cavities. The operating mode where electrolyte is circulated through both the oxygen and water compartments should give the optimum performance obtainable with this type of cell, while operating with continuously circulating electrolyte through the water cavities only, should give optimum performance for the static vapor feed mode. The first mode of operation should give only slightly improved performance over the latter for a current density up to 108 mA/cm^2 (100 A/ft^2).

The 48-hour continuous acceptance tests showed the module to be capable of giving excellent performance from a cell voltage point of view at current densities of 108 mA/cm^2 (100 A/ft^2). Typically, module voltages were between 22.8 and 23.5 volts per module at 108 mA/cm^2 (100 A/ft^2) at temperatures between 344 - 350°K (160-170°F). This gives a cell voltage range of 1.52 to 1.57 volts per cell. A comparison of performance when circulating liquid through both oxygen and water cavities and the water cavity only showed that at 5 amps or approximately 45.2 mA/cm^2 (42 A/ft^2), the average module voltage was 21.6 with liquid circulating through both oxygen and hydrogen cavities and 22.0 volts for liquid circulating through the water cavity only.

A flow rate versus pressure drop test with water flowing through the feed cavities was conducted for each module undergoing the 48-hour acceptance test. The data showed pressure drops in excess of 6.89 x 10^2 N/m^2 gage (1 psi) for flow rates in excess of 2 liters/min.

The data for the 48-hour acceptance test show that the modules are capable of excellent voltage levels. The mode of operation, however, that was used employed continuous circulation of electrolyte through the feed compartments and did not duplicate the feed and operating modes as was planned originally for the 90-day test, nor those used in the subsequent operation at MDAC.

5.4.5 Conclusions of Review of Past Performance of SVFU Modules

Based on a review of the data available from the 100-hour acceptance test, the 90-day test, the refurbishment test, and the 48-hour acceptance test, the following conclusions are drawn:

1. The total self-contained system for the 90-day test application was, by design, unable to operate in the mode specified. Satisfactory performance in excess of several hours was impossible. The major cause of this shortcoming was the location of the water addition point to the circulation loop. The location chosen resulted in several hundred cc's of electrolyte being fed to the modules before water could be fed.

   With modules installed in a self-contained system and with an intermittent circulating mode of operation utilized, the point of feed water addition must be as close to the individual modules as possible to minimize concentration buildups in the feed compartments. Ideally, a separate water feed port with separate internal manifold is judged best for modules using the static water feed and intermittent electrolyte circulation concept.

2. The system as originally designed is capable of operating with satisfactory performance if electrolyte is continuously circulated through the feed compartments. In this mode, continuous operation for longer duration is possible at the production rate of 3.63 Kg O_2/day (8 lb O_2/day).

3. Based on the data presented, long-term operating problems of the system and/or modules may have been masked by the major short-term failures encountered. Long-term operating capabilities of the system and modules can, therefore, not be assessed.

4. The system was allowed to operate with individual cells showing 0 volts or voltages less than 1.3 volts. The system was also allowed to operate with the anode and cathode of a cell electrically shorted by an external jumper in order to "remove a poorly performing cell electrically from the stack," (as recommended by the original manufacturer). This mode of operation is extremely hazardous to both personnel and equipment. A cell having 0 voltage and being in a module producing hydrogen and oxygen, with gas passages connected in parallel, indicates that the electrodes are either shorted or that an internal gas crossover exists. In the first mode hydrogen and oxygen combine resulting in currents in excess of 100 amps/cell and heat loads 40 to 50 times the heat load at design conditions. In the second mode the hydrogen and oxygen combine through direct mixing with temperatures possible in excess of 811°K (1000°F).

   The system did not have automatic shutdown provisions nor did instructions to operators exist to preclude operation at these dangerous conditions.

5. The circulation as originally specified by the manufacturer was required to remove gases that had accumulated within the liquid loop. The source of these gases could primarily be from stray electrolysis, inter-cell electrolysis, and dissolved gases entering with the feed water. No conclusive data was presented on quantifying this amount of gas liberated or purged. No evidence was found in the literature that demonstrated that the original manufacturer took necessary precautions to avoid electrical grounding of the

circulating loop within the system and hence decrease possibilities of stray electrolysis in the loop. The circulation frequency for the system as originally designed should have been dictated by electrolyte concentration buildup within the cavities, not by gas accumulation.

6. The conclusions and recommendations drawn by MDAC personnel with respect to shortcomings in peripheral equipment as supplied in the WES for the 90-day test data are concurred with and are judged to be beneficial for future system operation by Life Systems, Inc.

5.5 Unit Integration

Prior to and during acceptance testing at LSI, the SVFU modules, system, and test stand were integrated and operated to insure that all components worked properly without interface problems. Components included in the integration were the SVFU, oxygen accumulator assembly, signal conditioning console, power supply unit, coolant circulating loop, product gas vent system, Dymec Data acquisition unit, Kennedy magnetic tape recorder, computer/ Dymec Interface unit, CDC 8090 computer and CDC 1612 on-line printer. Initial tests were conducted for periods of 2 to 8 hours per day until all the apparent anomalies were worked out and all units functioned smoothly including the computer software program. Part of the integration was to establish procedures and gain experience in operating all components of the new system and ancillary equipment. The culmination of the integration effort and short term testing was a 100-hour checkout test.

5.6 Checkout Testing

Two separate checkout tests were conducted on the SVFU. The first test was a 100-hour test that was conducted at the end of the integration efforts. The second was termed the 80-hour checkout test. The major difference between the two tests was the method of water feed. In the 100-hour test the water was supplied on a pressure demand principle directly into the intermittently operating electrolyte circulation loop. In the 80-hour test the water was supplied on a pressure demand principle directly into the water cavity manifold of each module. Also circulating pump operation frequency was 30 seconds each 30 minutes in the 100-hour test and 2 minutes each 6 hours in the 80-hour test. The following paragraphs describe the testing conducted under each test and the results obtained.

5.6.1 100-Hour System Checkout

This test, all integration leading up to this test, all trouble shooting, and procedures preparation for this test were performed under the sponsorship of the McDonnell Douglas Astronautics Company Independent Research and Development funding and in-house capital funding.

The 100-hour checkout test of the static vapor feed water electrolysis system and data monitoring and safe-control system was performed during the period 0900, 24 August, 1971 through 1300, 28 August, 1971. The electrolysis system utilized only module number one in lieu of the intended 3 modules because all other modules were undergoing acceptance testing at a subcontractor facility. Nevertheless one module was capable of supplying sufficient signals to the monitoring system to exercise its operation and two of the 4 safe-control shutdown modes could be tested. That is, either a module shutdown or total system shutdown rather than three separate modules or the total system. The safe control system could terminate module operation for any of the following reasons: cell overvoltage, module overvoltage, or module overtemperature. Approximately 100 channels of data were normally monitored by the data acquisition system when 3 modules were operating; with only one module operating approximately 60 channels were being exercised. This included 21 channels from the module and 38 channels of data from the remainder of the system and from the calibration channels.

During the 100-hour period the system was operated at 6.89×10^4, 20.6×10^4 and 34.4×10^4 N/m^2 gage (10, 30, and 50 psig) and 6, 10 and 14 amperes. At the 20.6×10^4 N/m^2 gage (30 psig) level the system was also operated at 0.5 and 11.3 amperes under special conditions. These special conditions included analog control of current by a rise and fall of pressure in an oxygen accumulator tank and simulation of orbital operations by having nominal current levels during sunlight portion of the orbit (53 minutes) and 0.5 amperes current during the night portion of the orbit (40 minutes). Periods of operation at any condition varied from a minimum of 8 hours to a maximum 16 hours.

Overall the operation of the system was very satisfactory. A number of shutdowns occurred but were mostly attributable to human error and shortcomings in procedural evolutions. Indicated problem areas included: a) separate vent sequence procedures, b) current controller electronics affected by condensation, c) stray electrolysis in the electrolyte loop, and d) settings of the differential pressure switches.

5.6.1.1 Configuration of the Test

During normal operations feed water was pumped to an accumulator from a supply source every hour. The pump operated for approximately 30 seconds. Industrial distilled water as received from the supplier was used without any pretreatment. From the accumulator, the water was supplied on a pressure demand principle directly into the electrolyte circulation loop. Each half hour an electrolyte circulation pump would operate for 30 seconds to remove any gases trapped in the cells of the module and reduce the concentration of electrolyte in the water matrix of the cells. This period was sufficient to also move the lower-concentration electrolyte from the two-phase separator into the water matrix of the modules. The water in the water matrix was transferred as a vapor to the electrolyte matrix where it was electrolyzed into hydrogen and oxygen. The O_2 was then supplied to an accumulator or dumped overboard depending on the operating configuration of the system. The H_2 was dumped overboard. Both gases generated by the system were passed through a condenser and their respective back-pressure regulator before going through water bubblers and then wet-test meters to monitor quantity of flow and KOH carryover. Water vapor condensed from the O_2 and H_2 gas was fed back to the electrolysis modules. Pressure differentials maintained during the test are: hydrogen, 3.44×10^3 to 6.89×10^3 N/m^2 (0.5 to 1.0 psi) above oxygen; and oxygen, 6.89×10^3 to 10.33×10^3 N/m^2 (1.0 to 1.5 psi) above electrolyte.

Current to the electrolysis module was regulated by one of 3 methods depending on the mode of operation. Normally, a current control potentiometer on the front panel fixed the current to the module. During analog control the current was regulated by sensing the oxygen accumulator pressure downstream of the unit and using this signal to adjust the production rate to meet system demands. For orbital simulation a timer controlled the day/night cycle; day current was fixed by the current control potentiometer, and the night current by a false signal that simulated a high oxygen accumulator pressure, thus reducing current to approximately 0.5 amperes.

A data acquistion and performance monitoring system was used that monitored the system operation and displayed pertinent data on the unit. The system consisted of a signal conditioning console, a Dymec data acquisition unit with a Kennedy magnetic tape recorder, an interface module, a CDC 8090 computer and a CDC 1612 on-line printer. Approximately 200 channels of data from two electrolysis units could be monitored. For this test only one system was in operation and only 60 of the 100 channels were activated due to the use of only one electrolysis module. Data was recorded on magnetic tape at one-minute intervals. The raw data into the data acquisition system was recorded by the system and simultaneously delivered through the computer interface module to the computer for comparison of each data signal with a preset value in memory. If a parameter was out of tolerance, a signal was returned to the interface module which sent a control signal back to the malperforming portion of the electrolysis system. In this manner it was possible to shut off a single module or the entire electrolysis system.

A schedule of the 100-hour checkout test is shown in Table 5-5. Each pressure level was maintained for a minimum of 8 hours and each current level for a minimum of 24 hours. Two 8-hour periods of analog control of current were also employed. Orbital simulation for 8 hours was conducted. Finally, 16 hours of steady state operation at nominal conditions was conducted. The daylight portion of the orbital simulation was approximately 53 minutes

TABLE 5-5. 100-HR CHECKOUT TEST SCHEDULE

1 Module

Hours on Test	0	10	20	30		40	50
O_2 Prod. Rate Kg/Day (lb/day)	1.50 (3.3)			0.64 (1.4)			1.09 (2.4)
Ave. Current Per Mod. (Amps)	14			6			10
System Press. N/m^2 gage (psig)	20.6×10^4 (30)	34.4×10^4 (50)	6.89×10^4 (10)	6.89×10^4 (10)	20.6×10^4 (30)**	34.4×10^4 (50)	34.4×10^4 (50)

	60	70	80	90	100
	2.4		*	2.67	
	10		*	11.3	
	20.6×10^4 (30)**	6.89×10^4 (10)	20.6×10^4 (30)	20.6×10^4 (30)	

** Analog Current Control with O_2 Accumulator

* Orbital Simulation - 8 Orbits

Hour of Test	1	2	3	4	5	6	7	8	Etc.

Orbit Period	Day (50 Min)	Night (40 Min)	Day	Night	Day	Night	Day	Night	Day	Night	
O_2 Prod. Rate Kg/day (lb/day)	1.21 (2.67)	0.06 (0.13)	1.21 (2.67)	0.06 (0.13)	1.21 (2.67)	0.06 (0.13)	1.21 (2.67)	0.06 (0.13)	1.21 (2.67)	0.06 (0.13)	
Ave. Current Per Mod. (Amps)	11.3	0.6	11.3	0.6	11.3	0.6	11.3	0.6	11.3	0.6	

and the night or dark-side portion of the orbit was approximately 40 minutes. The current ranged between 11.3 and 11.6 amperes during day light and 0.5 to 0.6 amperes during dark or night periods. Analog control of current caused the current to range between 9.0 and 10.1 amperes to maintain accumulator pressures with a fixed bleed rate on the accumulator.

5.6.1.2 Performance Data

The time record of module and system performance is shown on Figure 5-38. (11 pages). This curve includes module voltage, module current, high and low temperatures in the module, and cell voltages for cells 2, 6, 10 and 14. All data was recorded at 1 minute intervals and printed and plotted at 10 minute intervals. The curve also contains notes providing specific information about special events such as pressure levels, usual O_2 pressure, frequency of venting the 2-phase separator and quantity of gas vented from the separator. Hydrogen pressure was normally 3.44×10^3 to 6.89×10^3 N/m^2 gage (0.5 to 1.0 psig) greater than O_2 pressure and electrolyte pressure was normally 6.89×10^3 to 13.78×10^3 N/m^2 gage (1.0 to 2.0 psig) less than O_2 pressure. Any time a cell other than the 4 specific cells previously mentioned appeared to be acting irrational, that cell voltage was added to the plot. This occurred only once during the test; cell 15 was added to the curve for the testing period of 14 through 24 hours. Whenever a shutdown occurred during the test period the system was immediately restarted to get as much operating time as possible during the 100 hours. Necessary corrective action was taken to prevent an immediate repeat of the problem causing shutdown.

At the start of the test difficulty was encountered with the current channel for module position 1. It was not until 19 hours into the test that module position 1 current data was shifted to module position 3 current channel. From that time on current data was printed by the data acquisition system. The problem was somewhere between the electrolysis system and the data printer.

The major drops in temperature that appear at various intervals throughout the 100-hour period were directly related to the operation of the circulation

FIGURE 5-38 - TIME LINE OF PERFORMANCE (PAGE 1 OF 11)

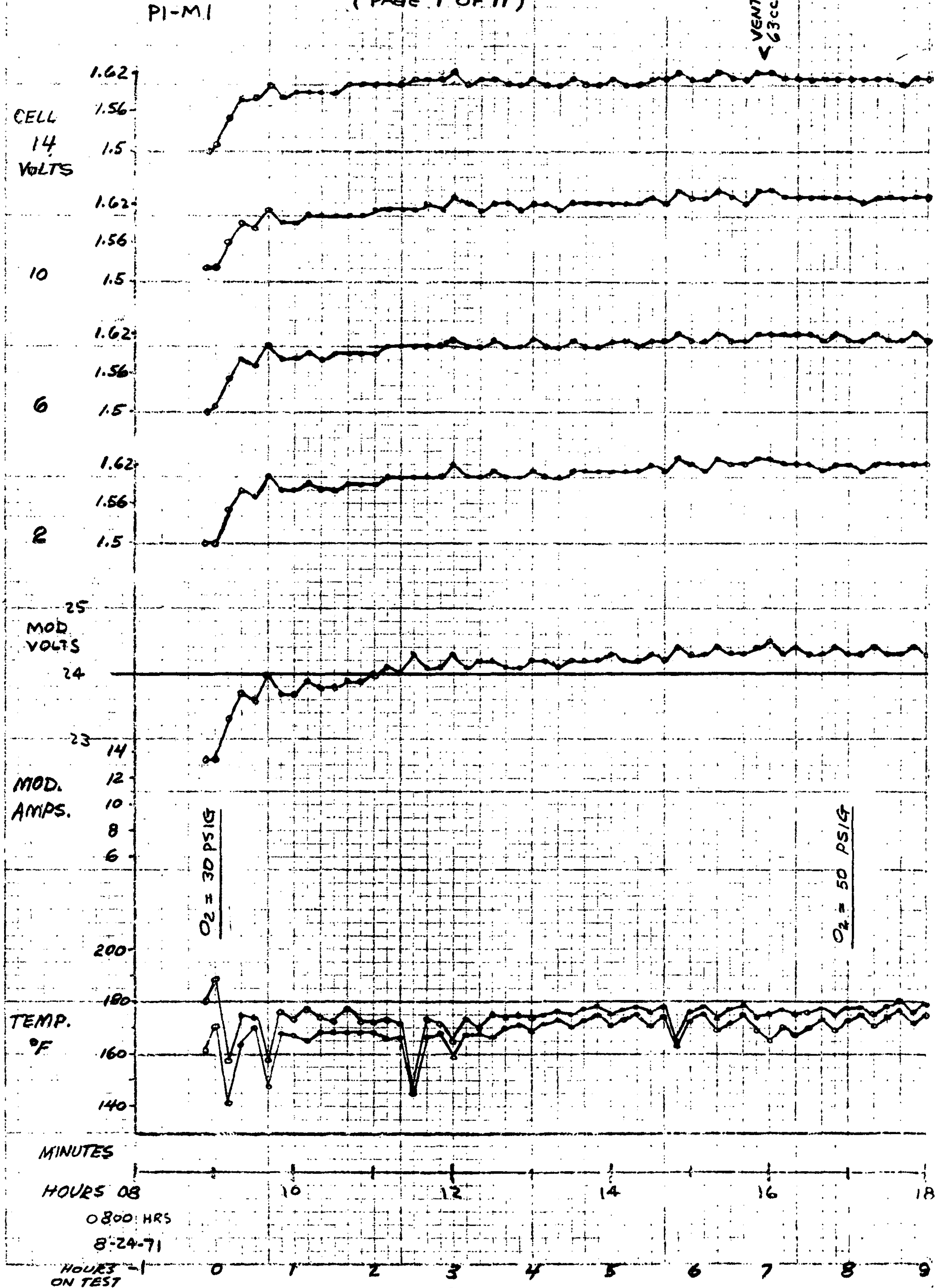


FIGURE 3-38 (CONTINUED)
(PAGE 2 OF 11)

PI-MI

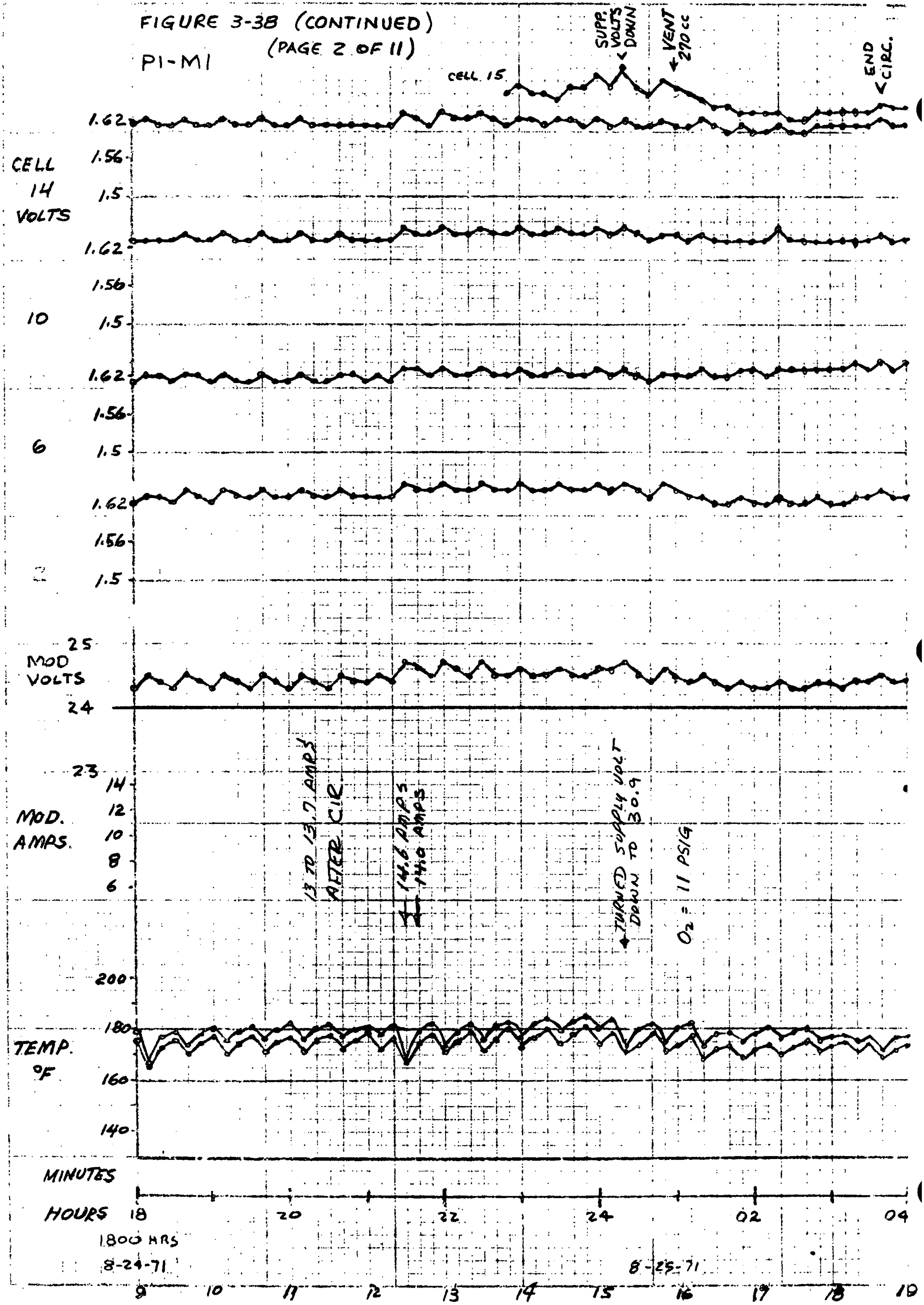
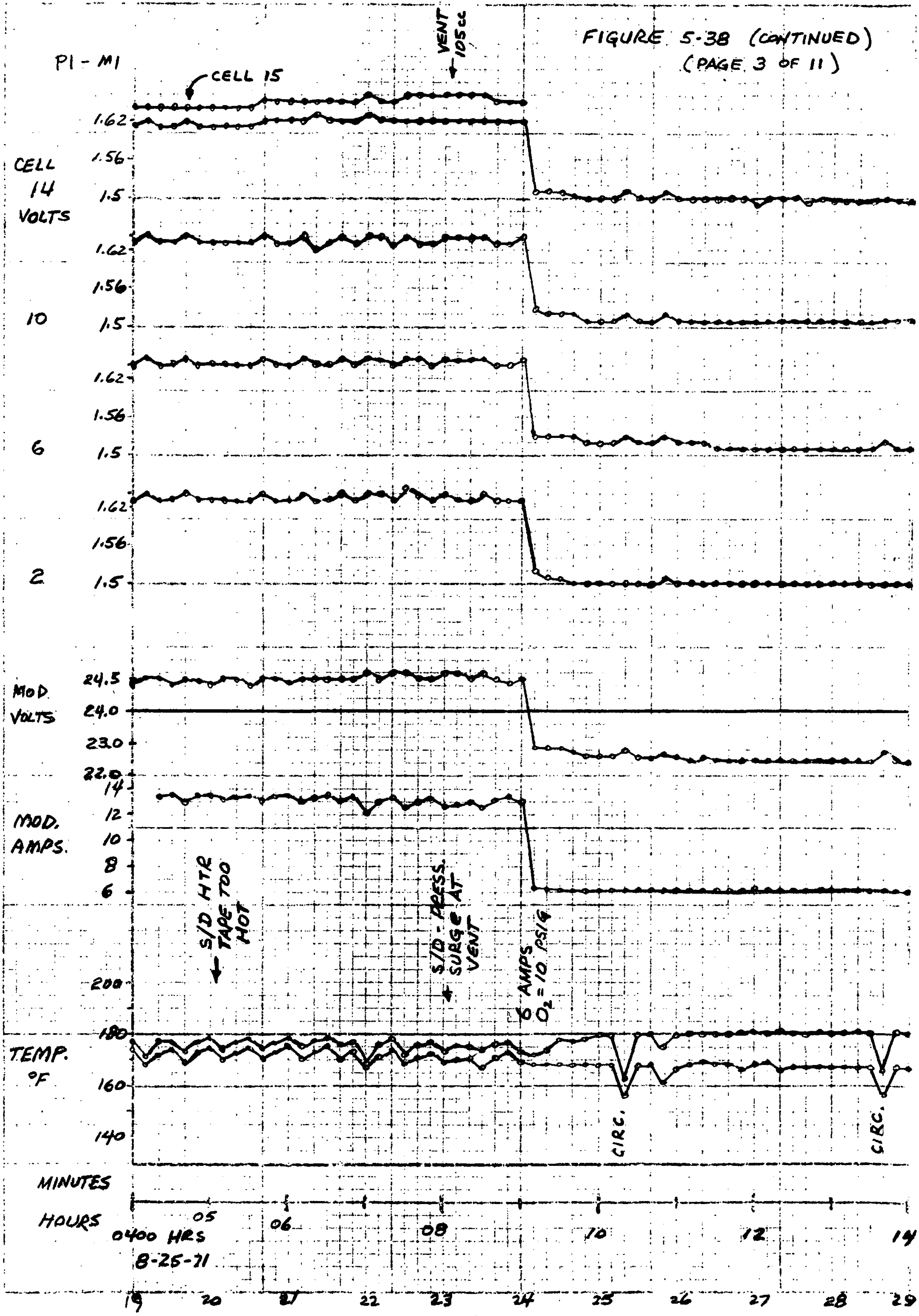


FIGURE 5-38 (CONTINUED)
(PAGE 3 OF 11)



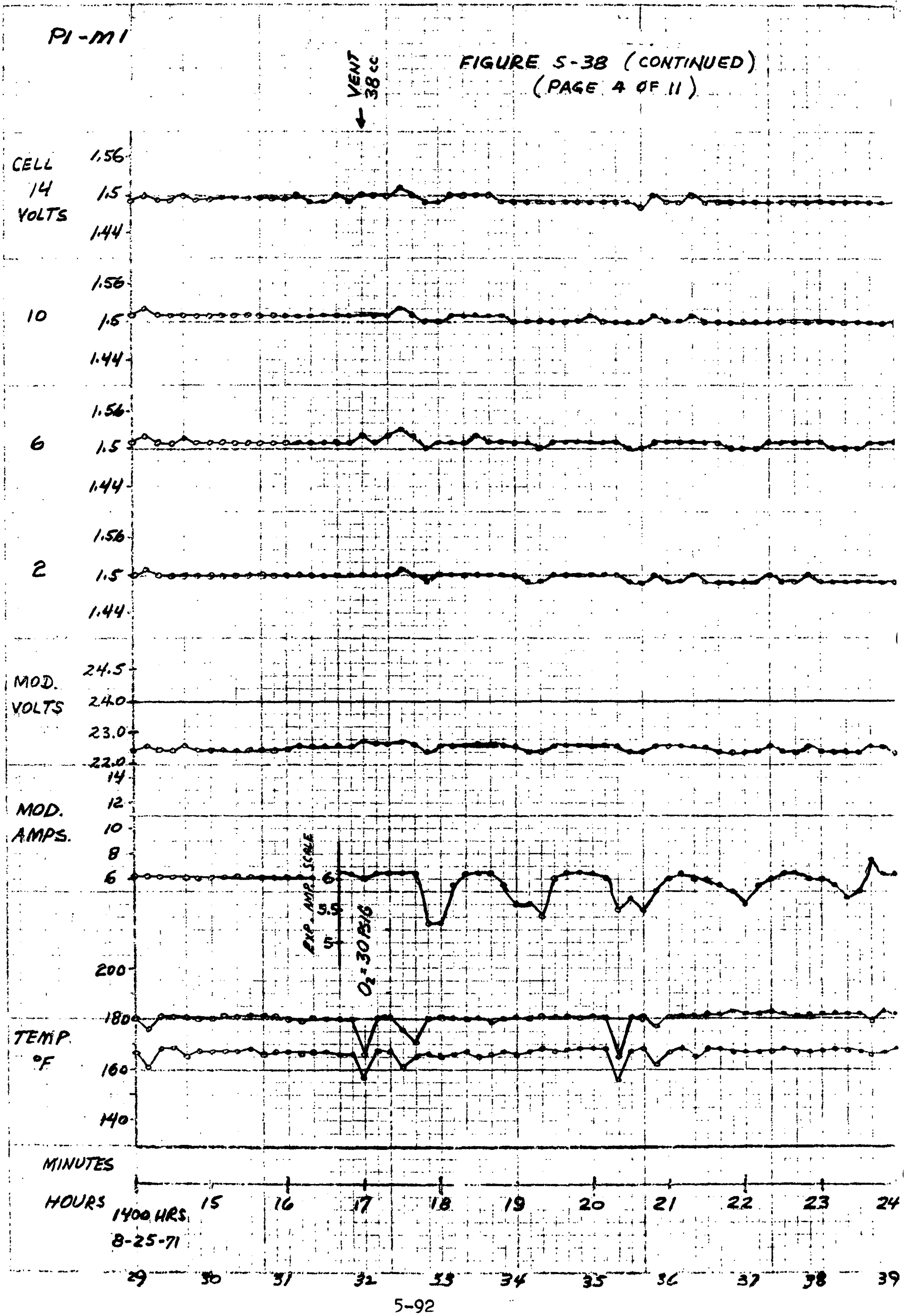
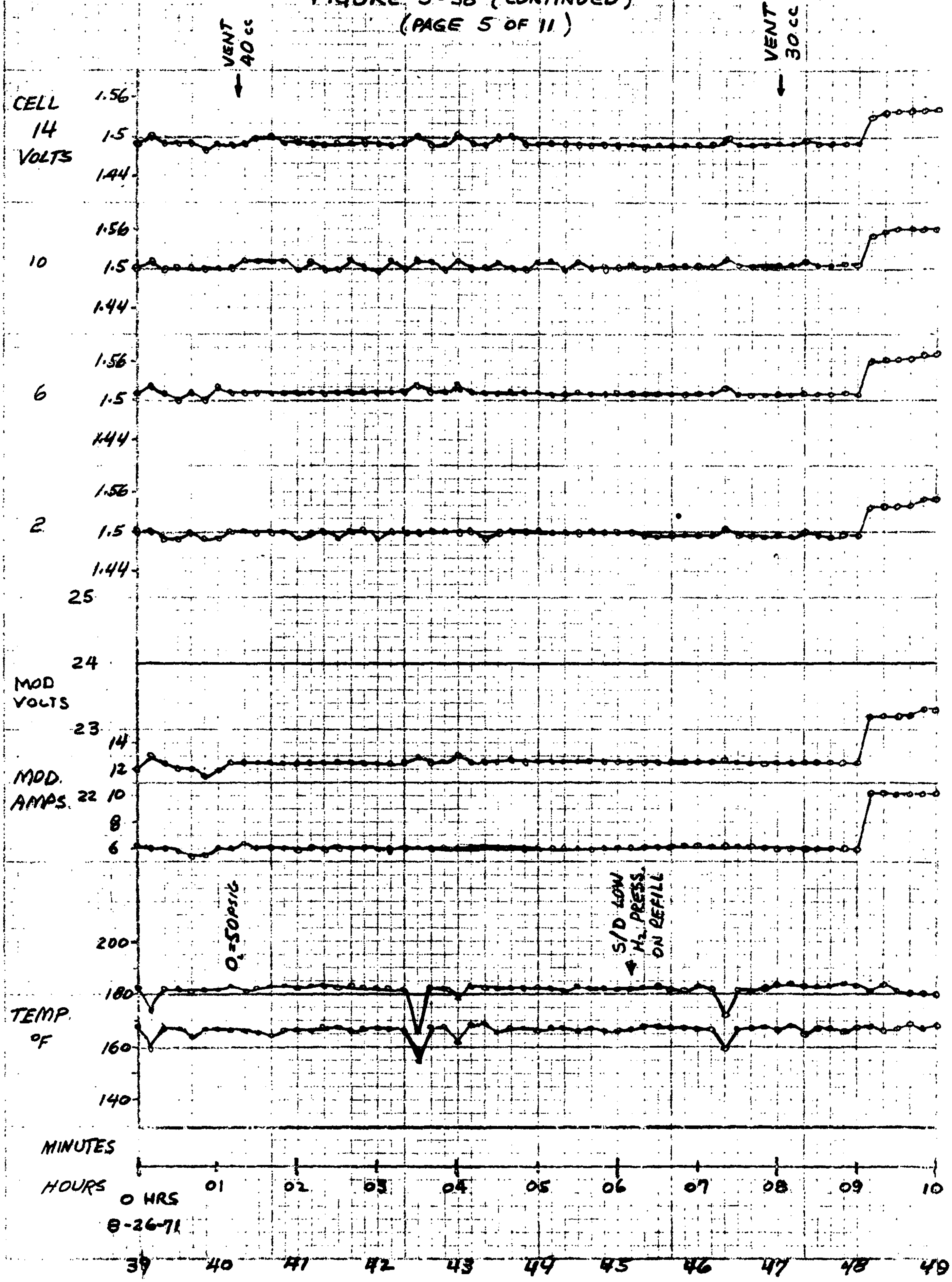


FIGURE 5-38 (CONTINUED) (PAGE 4 OF 11)

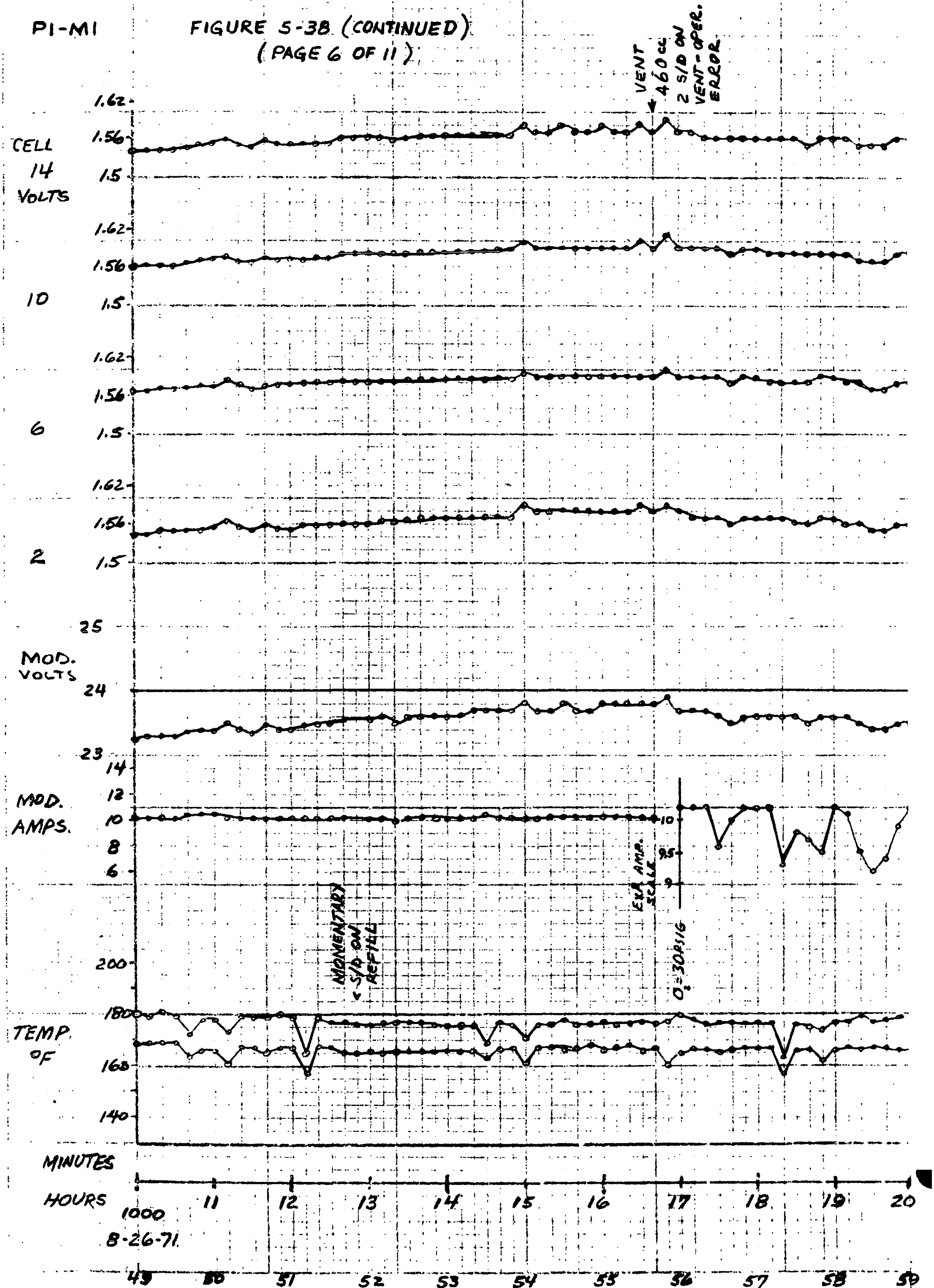
P1-M1

FIGURE 5-38 (CONTINUED)
(PAGE 5 OF 11)



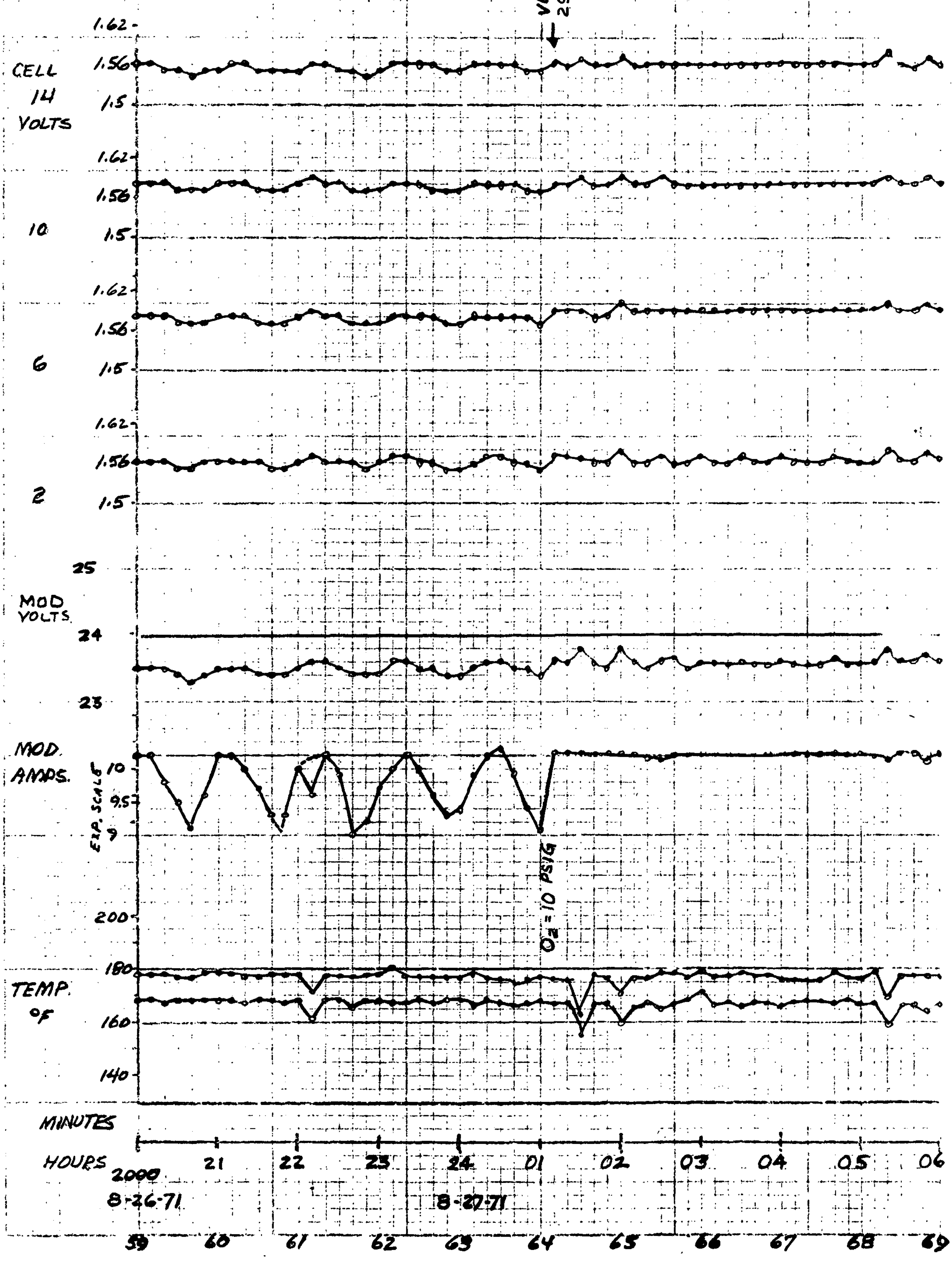
PI-MI

FIGURE 5-38 (CONTINUED)
(PAGE 6 OF 11)



PI-MI

FIGURE 5-38 (CONTINUED)
(PAGE 7 OF 11)



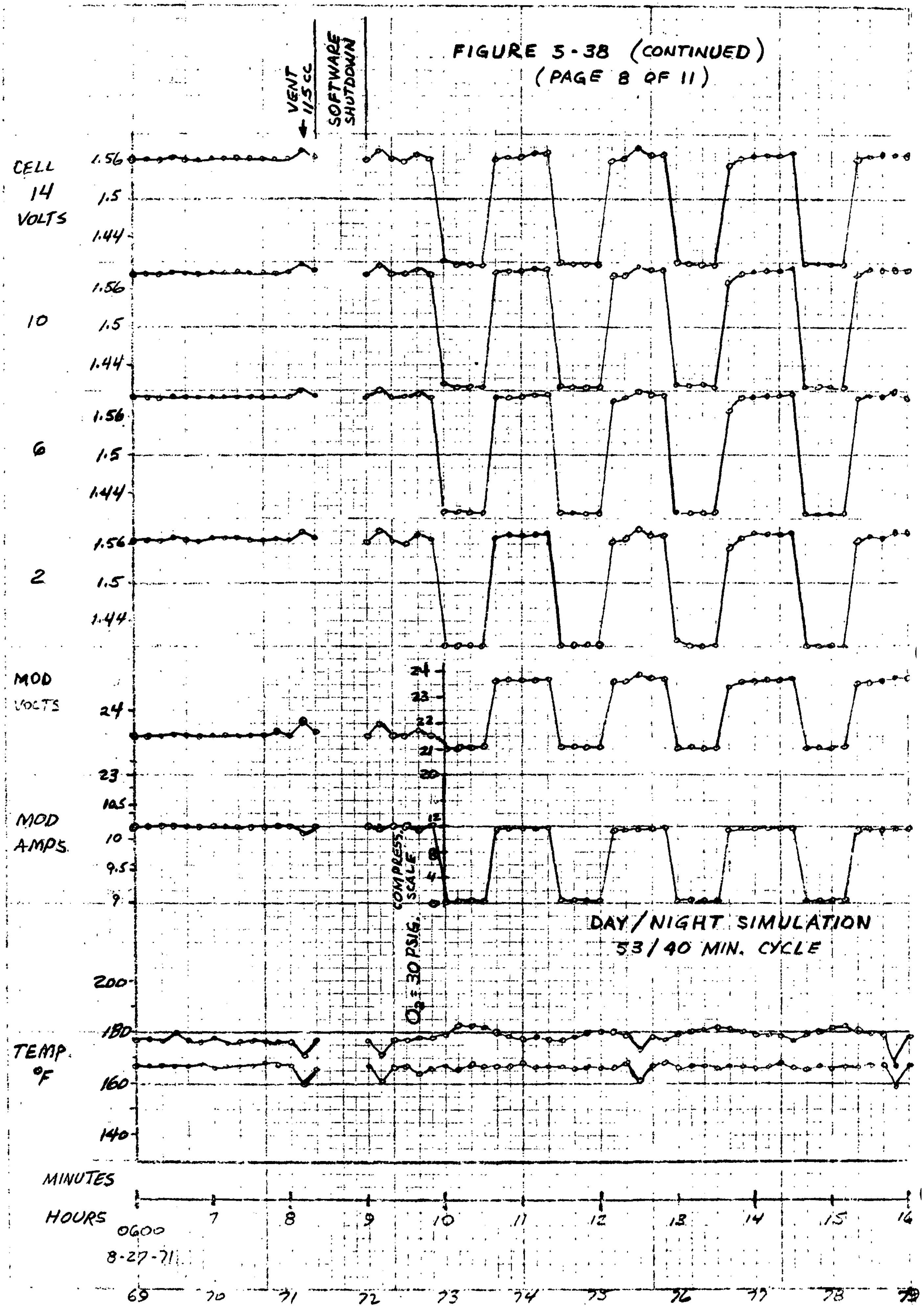


FIGURE 5-38 (CONTINUED)
(PAGE 8 OF 11)

4

P1-M1

FIGURE 5-38 (CONTINUED)
(PAGE 9 OF 11)

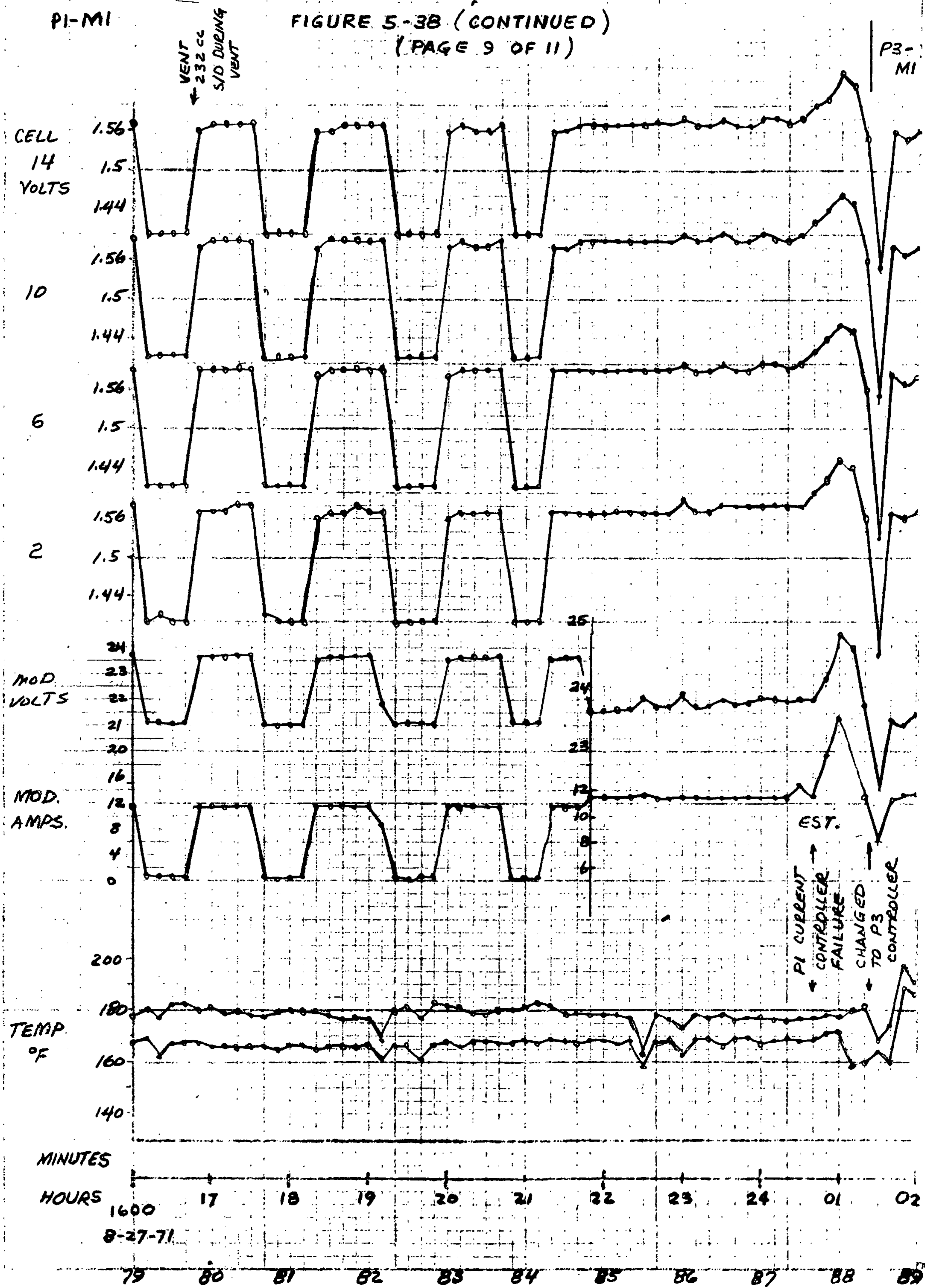
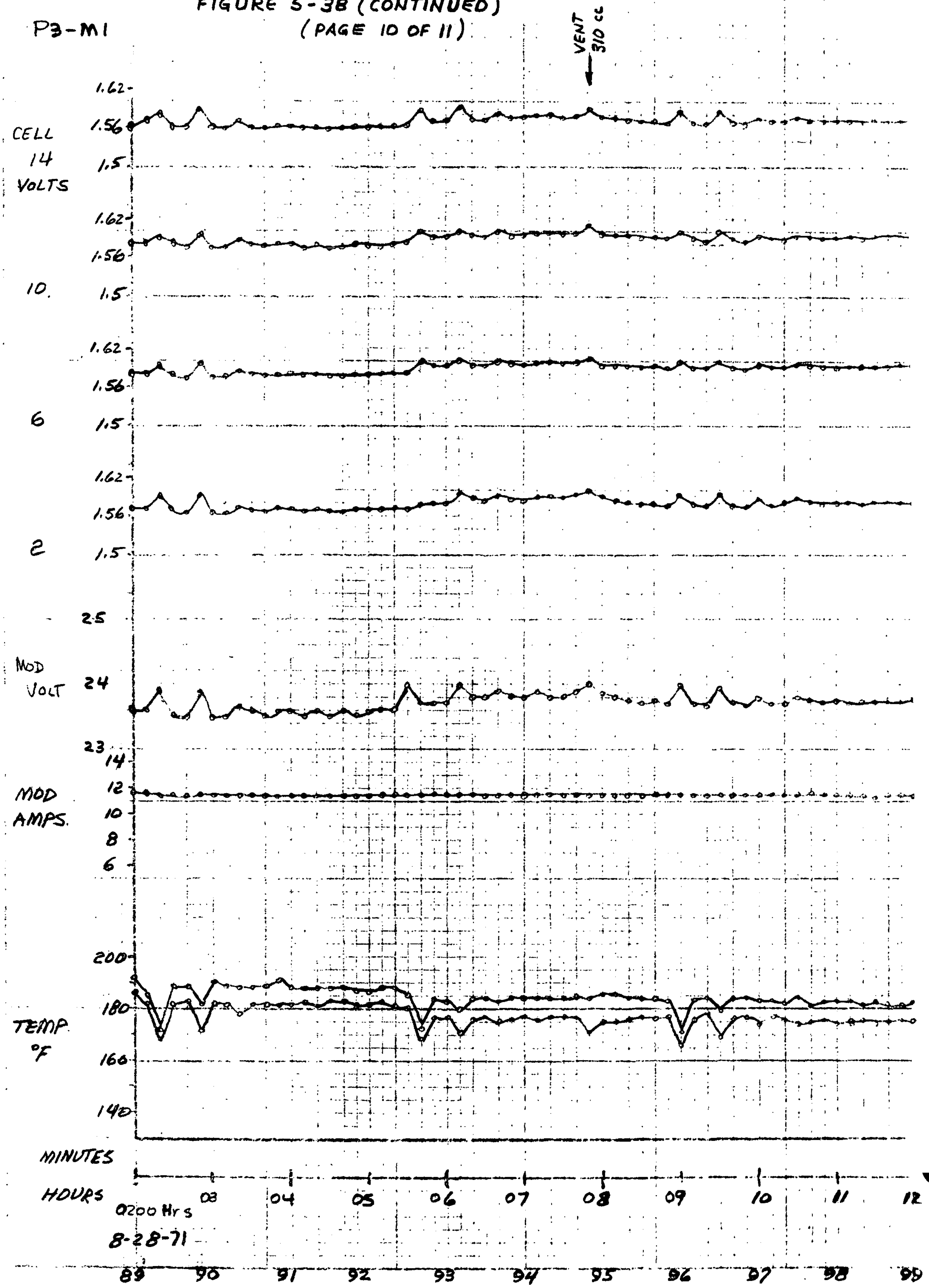
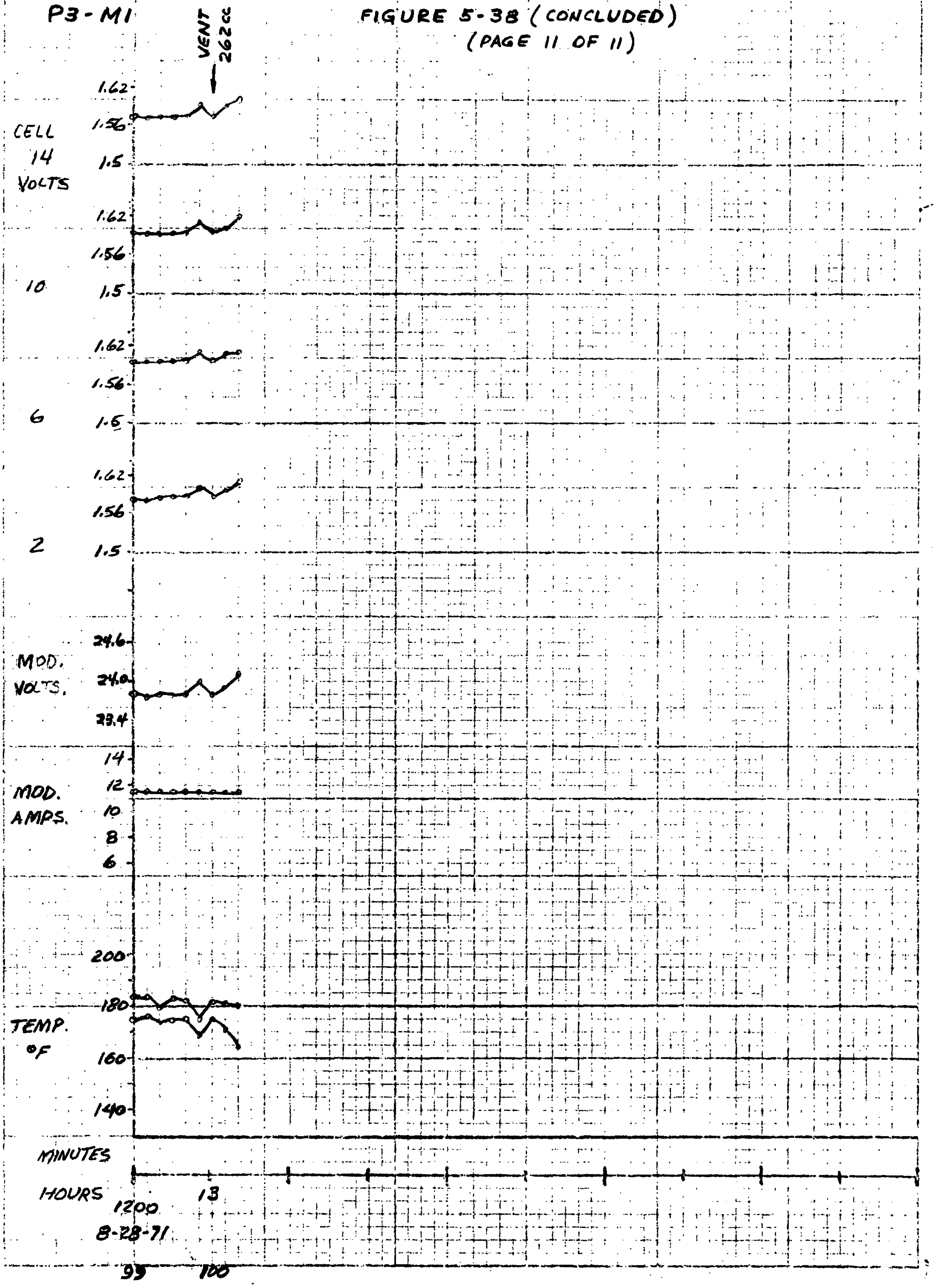


FIGURE 5-38 (CONTINUED)
(PAGE 10 OF 11)



P3-M1

FIGURE 5-38 (CONCLUDED)
(PAGE 11 OF 11)



pump. This pump normally operated 30 seconds approximately every 30 minutes. The pump operation and data scanning were not at even intervals; consequently the effect of pump operation does not appear uniform on the plot.

Stray electrolysis and/or cross leaks in the module caused an excessive amount of gas to accumulate in the 2-phase separator. The quantity was such that it necessitated venting the separator at 8-hour intervals. A number of places on the curves show the effect of too much gas in the system and rapid recovery of the system after venting the excess gas. The recovery of cell 15 and reduction of module voltage at 16 hours is a good example of this phenomena. Another example occurred at 56 hours of testing where 460 scc's of gas were vented.

A problem of current limiting was evident when operating at 14 amps. To maintain the high current it was necessary to increase the input voltage to 31.2 volts. When cell 15 voltage began to increase and eventually cause a shutdown the input voltage was reduced to 30.9 and the separator vented. This had the effect of bringing cell 15 back into tolerance but the average current was only 13.5 amperes rather than the desired 14.1 amperes level. Analysis later showed the current limiting phenomena to be caused by the design of the current control circuit. Current limiting could be minimized by operating at a supply voltage of 32 vdc.

Table 5-6 shows a list of all the shutdowns that occurred during the 100-hour test. It should be noted that 8 of the recorded 10 shutdowns were caused by improper procedures on the part of the operators. Although these shutdowns were undesirable they provided an ideal opportunity to checkout the automatic shutdown of the module and system by the safe-control safety circuits. Also note that all but one of the human errors were associated with regulator settings and occurred before hour 56 of the test. Four shutdowns of this type occurred when operating at 3.44×10^5 N/m^2 gage (50 psig), the most sensitive differential pressure condition. After the 100-hour test, the separator vent sequence was revised so as not to require adjustment of operational regulators during venting. Straps were added to reinforce the switch mountings inside the differential pressure switch housing to insure that an out-of-tolerance condition would not affect switch adjustment.

Table 5-6

HISTORY OF SHUT DOWNS DURING 100-HOUR CHECKOUT TEST

Test Hours	Type of Shutdown	System Condition O_2 Press	System Condition Amps	Cause	Corrective Action	Reason for Shutdown
1520	Computer, cell is @ 1.7 volts	34.6×10^4 N/m^2 gage (50.3 psig)	13.0	Cell Voltage high	Lowered supply volt to 30.9	Computer sample came just after circulation
2000	Computer, system shutdown, system temperature (13), module H_2O in @ 369°K (204°F)	7.58×10^4 N/m^2 gage (11 psig)	13.47	Human error	Lowered heater tape input power to 50 watts	Boost heater tape had too much power and computer limits too low.
2305	ΔP switch, Low H_2O Pressure	7.58×10^4 N/m^2 gage (11 psig)	12.5	Human Error	Adjusted regulator PR 2 to match H_2O pressure	Venting of separator gas caused rapid decay in H_2O pressure
4510	ΔP switch, Low H_2 pressure	35.6×10^4 N/m^2 gage (51.8 psig)	6.1	Human error, improper regulator setting	Adjusted H_2 regulator pressure to 6.89×10^3 N/m^2 (1 psi) above O_2	Refill caused momentary pressure surge.
5150	ΔP switch, high H_2O pressure	34.8×10^4 N/m^2 gage (50.5 psig)	10.0	Human error, improper regulator setting	Adjusted regulator for 6.89×10^3 N/m^3 (1 psi) ΔP	Refill caused momentary pressure surge
5606	ΔP switch, Low H_2O pressure	34.4×10^4 N/m^2 gage (50 psig)	10.0	Human error	Adjusted regulator PR2 to match H_2O pressure	Venting of separator gas caused rapid decay in H_2O pressure

Table 5-6 (continued)

HISTORY OF SHUT DOWNS DURING 100-HR CHECKOUT TEST

Test Hours	Type of Shutdown	System Condition		Cause	Corrective Action	Reason for Shutdown
		O_2 Press	Amps			
5606	A second ΔP switch, Low H_2O Pressure	34.4×10^4 N/m^2 gage (50 psig)	10.0	Human error	Adjusted regulator PR 2 to match H_2O pressure	Venting of separator gas caused rapid decay in H_2O pressure
7120	Computer, software problem	8.79×10^4 N/m^2 gage (12.75 psig)	10.0	Human error	None	Data system tape rewind was improperly accomplished by operator
7945	ΔP swtich, Low H_2O pressure	21.3×10^4 N/m^2 gage (31 psig)	11.3	Human error	Adjusted regulator PR2 to match H_2O pressure	Venting of separator gas caused rapid decay of H_2O pressure
8800	Manual shutoff	21.9×10^4 N/m^2 gage (31.8 psig)	17	Regulator #1 control lost	Moved module to position #3	Modure current was uncontrolled requiring manual shutoff.

Limits of cell voltages were increased to 1.75 volts to eliminate shut-downs after circulation when operating at high amperage-levels. Post-test checkout did not reveal the problem with position 1 current controller that occurred at test hour 88. It was thought that this failure was due to isolation of the power transistor from the coldplate, and/or secondary breakdown of the transistor. Both transistors in the number 1 current control position were replaced and the coldplate cleaned and insulated to prevent future occurrances.

During an 8-hour period from 1700 on 26 August 1971 the analog current control system was in operation as shown on Figure 5-39. Current varied from a high of 10.2 amperes to a low of 9.0 amperes as the oxygen accumulator cycled between 16.9×10^4 and 18.9×10^4 N/m^2 gage (24.5 and 27.5 psig). A pressure curve correlating with the current data could not be plotted on Figure 5-39 because the pressure data was not being collected by the data acquisition system at the time this test was performed. Visual observation indicated that when the pressure was high the current to the modules was low. Also as the pressure decayed the current level increased forming a sinusoidal curve that appeared to be a mirror image of the module ampere curve. Significant problems with the analog control circuit were not encountered, although it was felt that more flexibility and easier set-up would be attained if the slope of the current/pressure curve were flattened slightly. Electrical changes to accomplish this were implemented.

Orbital simulation was employed from 1000 to 2200 hours on 27 August 1971. The current was varied from 11 amperes during the day portion of the cycle to about 0.5 amperes in the night portion of the cycle. Day portion of the orbit was 53 minutes duration and the night portion approximately 40 minutes in length. This is shown on Figure 5-40. Problems were not encountered with this mode of operation. The orbital simulation seems to result in slightly reduced cell voltages during the day portion of the orbit compared to continuous operation at the same current level.

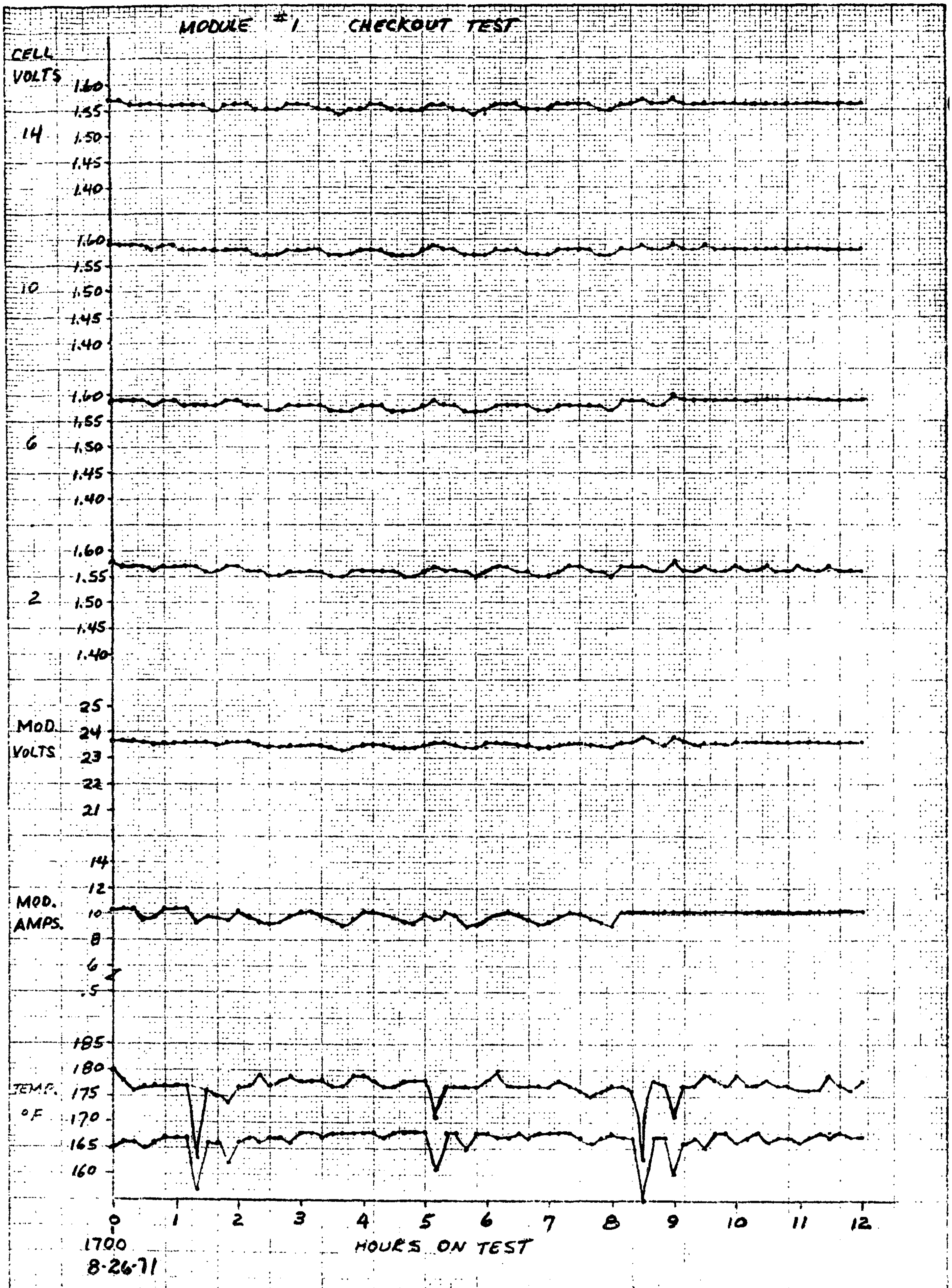
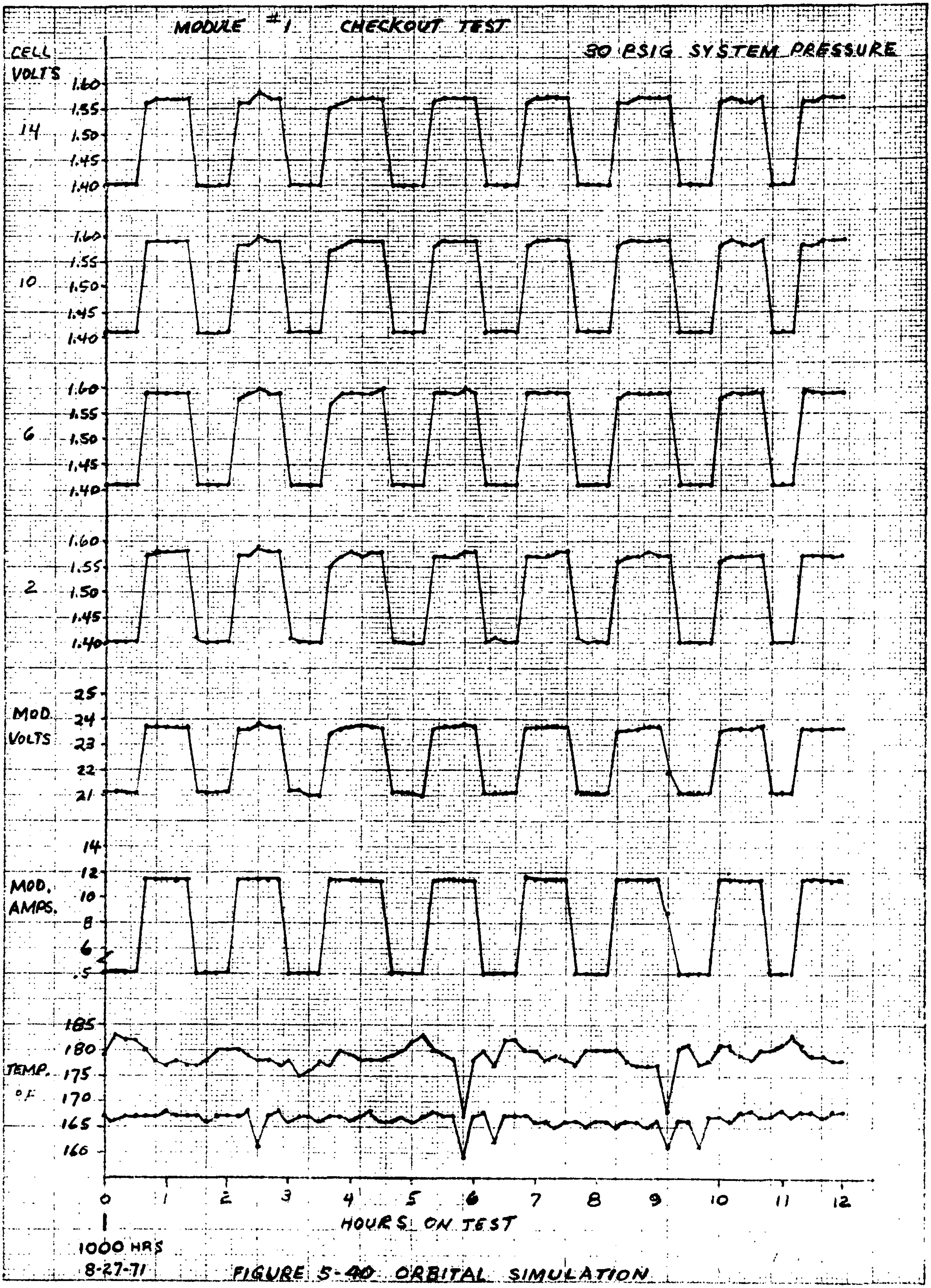


FIGURE 5-39 ANALOG OPERATION



MODULE #1 CHECKOUT TEST

30 PSIG SYSTEM PRESSURE

FIGURE 5-40 ORBITAL SIMULATION

5.6.1.3 Post-Test Analyses

After the completion of the 100-hour test period a number of analyses and comparisons were performed to more fully evaluate the performance of the system. These analyses and comparisons are presented in the following subparagraphs.

- Bubbler Water

All gas generated by the system passed through a water bubbler before entering the wet test meters for quantity measurements. The bubblers served two purposes, 1) to saturate the gas entering the wet test meter and 2) to trap any KOH carryover that might exist in the effluent gas streams. It was evident that the gas leaving the electrolysis system was not saturated as water had to be added to the bubblers to bring the water level up to the original level. Originally the bubblers were filled with distilled water that showed no traces of KOH. After the test the hydrogen bubbler had less than 0.01% KOH concentration and the oxygen bubbler had 0.01% KOH concentration. This represents an extremely low quantity of KOH carryover from the system but leaves the question open as to when the carryover occurred. That is, was the carryover continuous at a uniform rate or was it at a high rate early in the 100-hour period and then a lesser rate as time progressed? It was thought that later testing would resolve this question.

- Electrolyte Concentration

A sample of electrolyte removed from the system after the 100-hour test was determined to have a concentration of 31.7% KOH. The electrolyte concentration at the start of the 100-hour test was 31.4% KOH. The difference in initial and final concentration (0.3%) was within the expected range of sample to sample variation and experimental accuracy of the titration procedure. There was no evidence of electrolyte leakage during the 100-hour test period. Every effort was made to ensure that a fixed quantity of electrolyte salts stayed in the system during the test period.

- Limit Changes

Three changes were made in the shutdown limits for the system. All voltages are normally higher than identified by the module manufacturer when operating at low pressures and/or high current levels. The operation of the electrolyte circulating pump also causes perturbations on the cell voltages. Thus, it was decided, after consulting with Life Systems, Inc. personnel and after observing the recovery of cells operating at levels as high as 2.1 volts, that a maximum limit of 1.75 volts would be a more realistic value for module shutdown than the 1.70 volts originally selected. It was thought that this would significantly reduce the number of shutdowns expected and not cause irreparable damage to the cells.

The limits on the differential pressure switches represented the other two changes. The H_2O to H_2 switches were changed to 4.13×10^4 N/m^2 (6.0 psi) maximum hydrogen over water and 6.89×10^3 N/m^2 (1.0 psi) water over hydrogen. The O_2 to H_2 switches were changed to 2.76×10^4 N/m^2 (4.0 psi) maximum hydrogen over oxygen and 1.38×10^4 N/m^2 (2.0 psi) oxygen over hydrogen. It was felt that these limits were wide enough to prevent inadvertent tripping yet tight enough to prevent irreparable damage to the cells in the event of unit malfunction.

- Gas Venting

The two-phase separator required venting every 8 hours to prevent excess gas accumulation in the system and to prevent major changes in the electrolyte concentration in the circulating electrolyte loop. The source of this gas was thought to be some combination of cross leaks and/or stray electrolysis. Average gas accumulation rate within the system was 23.6 cc/hr.

At the conclusion of the 100-hour test, a cross-leak test was conducted on module 1. Helium was used to pressurize the hydrogen cavity. Tubes connected to the H_2O and O_2 cavities were placed under water and observed for bubbles. The module was found to have a cross-leak between the H_2 and H_2O cavity at a pressure differential of 2.76×10^4 N/m^2 (4 psid). A leak rate of one bubble per 7 seconds was observed at this pressure differential. At less than 2.76×10^4 N/m^2 differential (4 psid) no bubbles were observed from the H_2O discharge tube. No significant change in leak rate could be observed when nitrogen replaced helium as the pressurization gas.

Checks were made of system chassis resistance to ground, DC power bus to ground and DC return bus to ground. Also measured were chassis to component resistances for various components in the circuit. No anomalies were found. Power transistors in positions 1 and 3 were found to have relatively low resistance to chassis. These transistors were removed, the coldplate cleaned, new thermal compound applied, and new transistors installed in position 1. These efforts increased the resistance between the transistors and chassis.

Measurements were made of system chassis to ground potentials and module water fittings to frame (chassis) potentials under various operating conditions. Measurements of module water fitting potentials relative to DC supply and return were also made as were module water fittings potentials relative to module supply and return voltage. These measurements were recorded on strip charts to check for the possibility that some component operation affected the potentials. Only the periodic circulations were found to have any effect.

Spare components from the same incoming shipment of parts as those used in the electrolysis system were disassembled and placed in heated KOH solutions to check for noncompatible materials. Other than the shading rings of the Skinner solenoid valves which had been removed earlier, and a very slight initial attack on the 302 CRES springs of the check valves, no incompatible materials were uncovered. Items checked included: quick disconnects, check valves, manual valves, pump parts, CRES tubing, thermocouples, solenoid valves, fittings and turbine flowmeters.

The gas venting procedure caused 3 of the 10 shutdowns. Hence, it seemed desirable to improve the procedure to preclude unwanted shutdowns from this cause in future testing. Changing the procedure did not seem to eliminate the problem. The basic problem occurred when the operator pushed the separator vent button. This allowed gas and some electrolyte to escape from the separator into the separator traps. Simultaneously with the gas venting, the operator had to reduce system pressure by manipulating the electrolyte pressure regulator. This was necessary to keep all the fluids in the system within prescribed limits; otherwise, a shutdown would occur. If a small amount of gas were in the system the pressure would drop even more rapidly than it would with a large quantity of gas. Consequently, solving the problem of excess gas within the system would aggravate the problem of gas venting. The separator unit was isolated from the modules and the rest of the electrolyte plumbing by installing a manual valve in the electrolyte plumbing upstream of the separator. Downstream of the separator a check valve, already installed, prevented back flow of electrolyte. This arrangement was tried and found to be very successful. The system could be isolated, vented and brought back to system pressure with feed water without disturbing the differential pressure switches or the pressures within the module portion of the system. The time required to accomplish the venting procedure and the complexity of the separator venting procedure were also reduced significantly.

- Mass Balance Data

A summary of the mass balance for the 100-hour test period is shown below:

Total feed water consumed = 10.69 lbs (4850.0 grams)

Total H_2 produced = 6385.3 liters (517.8 grams)

Total O_2 produced - 3300.0 liters (4282.0 grams)

$$\text{Ratio; } \frac{H_2 \text{ produced as measured (liters)}}{O_2 \text{ produced as measured (liters)}} = \frac{6385.3}{3300.0} = 1.93$$

$$\text{Ratio; } \frac{O_2 \text{ produced, corrected (grams)}}{H_2 \text{ produced, corrected (grams)}} = \frac{4282.0}{517.8} = 8.27$$

$$\text{Ratio; } \frac{O_2 \text{ in feed water used (pounds)}}{O_2 \text{ produced as measured (pounds)}} = \frac{9.50}{9.54} = .996$$

$$\text{Ratio; } \frac{\text{Total gas weight, corrected (grams)}}{\text{Total water used, corrected (grams)}} = \frac{4799.8}{4822.33} = .993$$

H_2O trapped in gas produced - 27.67 grams

% error in H_2 production, assuming O_2 production is correct = -3.11% (by volume as measured)

% error in H_2 production, assuming O_2 production is correct = -3.38% (by weight as corrected for trapped liquid)

The oxygen to hydrogen production ratio, which should be 1:2 by volume and 8:1 by weight was found to be 1:1.93 and 8.27:1 respectively. This results in approximately a 3.25% negative error in the amount of hydrogen produced. Most probable explanation for the difficiency was a combination of human error in reading the hydrogen wet test meter, (H_2 meter scale was significantly more difficult to read than the O_2 meter scale), variations in accuracy of the wet test meters (± 1% as calibrated by MDAC, manufacturer claims ± 0.5% accuracy) and a very small amount of H_2 leakage. The ratio of oxygen in the feed water consumed to the O_2 produced of .996 and the ratio of the total gas produced to the total water consumed of .993, are well within the accuracy of the measurements.

Changes in the method of recording or calculating data were not recommended. Current efficiency was not calculated because of the limited current data recorded during the first hours of the test and the numerous short tests causing significant variations in the current levels. Nitrogen consumption was identified as an item to be added to the mass balance data.

5.6.2 80-Hour Checkout Test

The system was modified, subsequent to the 100-hour test, in accordance with instructions from the NASA program manager. The change required that the feed water be supplied on a pressure demand principle directly into the water cavity manifold of each module instead of into the electrolyte circulation loop. The second part of the change required that the circulating pump operate 2 minutes each 6 hours instead of 30 seconds each 30 minutes as was used in the 100-hour test. Check valves were installed in the water feed line and in the circulating electrolyte line to isolate the fluid cavities of the modules between circulation periods. This would insure water feed rather than electrolyte feed and prevent the increased concentration of KOH in the water cavity that would have resulted.

Following this change, the SVFU did not perform satisfactorily during the 80-hour checkout test. In fact, the performance was so poor that the second test readiness meeting was delayed two days due to the numerous problems encountered. At this meeting, a new checkout test schedule was prepared

Table 5-7 80-HOUR CHECKOUT TEST OPERATIONS

DATE	19-20 OCT	20 OCT	20-21 OCT	21-22 OCT	22-24 OCT	24 OCT	24-25 OCT	25-26 OCT	26 OCT
DURATION (HRS)	15.5	6.5	15.5	12	40	9	17	20	8
CURRENT PER MOD. (AMPS)	11.3	11.3*	11.3	11.3	11.3	14.1	11.3	11.3	14.1
PRESSURE N/m^2 GAGE (PSIG)	13.8×10^4 (20)	20.6×10^4 (30)	20.6×10^4 (30)	20.6×10^4 (30)	20.6×10^4 (30)	20.6×10^4 (30)	20.6×10^4 (30)	27.5×10^4 (40)	27.5×10^4 (40)
ACCUMULATOR	NO	NO	YES	NO	NO	NO	YES	NO	NO
MODULES	3, 4, 5	3, 4, 5	3, 4, 5	3, 4, 5	4, 5	4, 5	4, 5	4, 5	4,5
REASON FOR SHUTDOWN, IF ANY	High cell volts - P1-M3-C10		Flushing all mods, balancing concentration	Maintenance on facility pump	Mod 3 shutdown after 14 hrs. 2nd try on mod 3 was 13 hrs. Mod 2 tried, ran for 8.5 hrs.				

* ORBITAL SIMULATION

TOTAL RUNNING TIME: 144.5 hours
RUNNING TIME (3 MODS): 49.5
RUNNING TIME (2 MODS): 144.5
CONTINUOUS RUNNING TIME (2 MODS): 94 (as of 1600 26 Oct. 71)

for the SVFU and operating changes recommended. The new schedule required 50-56 hours of operation at 11.3 and 14.1 amperes, at 20.6×10^4 and 27.5×10^4 N/m^2 gage (30 and 40 psig), and with analog accumulator control. The results of the combined requirements are summarized on Table 5-7.

During the total test period of 12-26 October 1971, numerous shutdowns of either modules or the total system occurred. These can be summarized in the following categories: 12 were due to cell overvoltage, one was due to overtemperature of a module, 5 were because of improper differential pressure settings; 6 were from stray electronics noise that shut the whole system down, 7 were stray electronics noises causing module position 2 to shutdown, 6 were due to human error in taking samples of KOH, venting the separator or changing system pressures, and one was due to an electrical storm shutting off building power momentarily. Other problems encountered that caused poor performance were external leakage and vapor lock of the circulating pump, improper relief valve setting on circulation pump; stray electrolysis in module 5 and power limiting of module operation whenever module voltage exceeded 24.2 volts.

It was felt that all the above problems could easily be solved by improved operator performance, mechanical correction to the pump and increasing the voltage supply to the unit from 30 volts to 32 volts. The major unsolved problems were the cause of overvoltages in the cells, KOH accumulation within the H_2 cavity of each module, and identification of the correct electrolyte concentration to be used in the modules and the system.
A careful review of all the data and operating experience available between 12 and 21 Ocrober indicated that the modules should be flushed for 8 to 16 hours and that all cavities, O_2, H_2 and H_2O, should be flushed. A 30.0 to 30.5% KOH solution should be used. The system should be operated with a KOH concentration between 25.0 and 27.0%. These conditions were employed in lieu of the original requirement of 32.0% KOH in modules and system and the system showed a marked improvement in performance.

A number of modifications were made to the system during the period 12 - 28 October to improve the performance. These are briefly described below basically in chronological order of occurrence.

- Circulation pump internal relief setting was adjusted. The new pump which was installed had a higher setting than the original pump and was causing excessive differential pressures during operation. The original pump started to leak KOH just at the end of checkout testing. The result was a burned out armature winding.

- Timers were readjusted for a circulation once each 2 hours and water accumulator refill each hour. Initially, the circulation time was set for once each 6 hours.

- An orifice was installed in the ΔP switch feed line to eliminate shutdowns caused by pressure surges when the pumps operated.

- Check valves initially installed in the module inlet line for KOH circulation were moved to the outlet line to prevent backflow of KOH from one module to any other.

- The wiring on the electrolyte isolation solenoid valves was modified to open the valves only when the circulation pump was operating. Thus, the isolation solenoid valves served the same purpose originally intended for the inlet line check valves.

- Wiring on the separator cells was modified to turn the heaters off whenever the unit was shut down thus preventing excessive temperatures in the separator cells. A temperature of 367°K (200°F) was observed on one prior occasion.

- The electrolyte ΔP switch sensing line was moved to the accumulator feed manifold to provide better protection of the matrices against adverse pressure differentials. This was necessitated by the addition of the static feed mode of operation.

- The heating cycle of the inlet plumbing to the modules was increased from 30 to 45 minutes preceeding circulations to allow inlet plumbing temperatures to more closely approach module temperatures.

- A second adjustment was made on the circulation pump relief setting and pump head gasket was replaced.

- The water refill timer cam was readjusted for 30 seconds each hour as the cam had slipped and refill was only 30 seconds each 2 hours.

- A low-flow bleed line was added across the module inlet and outlet manifolds to allow complete bleed-down of the electrolyte plumbing during shutdown and prevent damage to the ΔP transducer.

- The initial charge concentration for the modules was changed from 32.0% to 30.5%. Overvoltages in cells seemed to be caused by too high a concentration in the electrolyte matrix.

- All modules were reflushed twice. Flushing procedure was changed to include O_2, H_2 and H_2O cavities and flushing was for a much longer duration to remove any trapped and residual KOH in the cavities.

- The system electrolyte concentration was changed from 30.5 to 26 ± 1%. It was felt that better performance was obtained with lower electrolyte concentrations in the system.

- Capacitors were added to the shutdown signal electronics to prevent undesired shutdown by stray signals of less than 25 milliseconds duration. This eliminated all unexplained stray shutdowns of the system and module position 2 that were mentioned before.

- Pulse counters and elapsed time recorders were added to cell heater circuits on each module to record parasitic power consumption.

- The thermal switches on front end plate of each module were disconnected to eliminate adverse cycling and allow temperature controllers to operate without interference. The two switches in series were overriding each other and causing undesired drift in module temperature levels.

As a result of the improved performance, the modified checkout test was performed smoothly on modules 4 and 5 only (in accordance with test committee approval) between 22 and 26 October 1971. Additional data on the performance of specific modules during this period may be found in Section 5.7.2.

5.7 Performance/Endurance Testing

The following paragraphs describe the overall performance of the static vapor feed water electrolysis unit during and just preceding the 26 weeks of testing. Following the descriptive material on the system is a section describing the performance of each module used during the test. This includes detailed performance curves developed to show trends. Next are sections showing special evaluations conducted on the unit during testing.

5.7.1 Overall Unit Performance

Figure 5-41 shows the overall performance of the static vapor feed unit during checkout testing and part of performance/endurance testing. The numerous shutdowns occurring between 12 and 26 October were explained in paragraph 5.6.2. Also explained were the changes made to the system to attempt to improve performance. Subsequent to 26 October each shutdown occurring, whether module or system, is shown and identified on the figures. Electrolyte concentration measurements taken during testing are also shown. Early in the program concentration measurements were taken at infrequent intervals. Later, when it was recognized that electrolyte maldistribution was the cause of numerous failures, concentration measurements were taken daily. After the automatic shutdown of module 3 on 28 October it was removed from the system and module 2 prepared for operation. Module 5 was manually turned off in order that it could be shifted from position 3 in the unit to position 2. Module 2 was then inserted in position 3. This module operated approximately 6 hours when cell 10 went out of tolerance due to cell overvoltage. It was decided to replace cell 10 as it appeared to be ultrasensitive and had caused previous shutdowns when all other cells in the module were operating uniformily. When the module failed, it was replaced with module 3 which was operated at 11.3 amperes for about 24 hours when instructions were received from the test committee to operate the module at reduced current to determine if a longer uninterrupted operating period could be obtained.

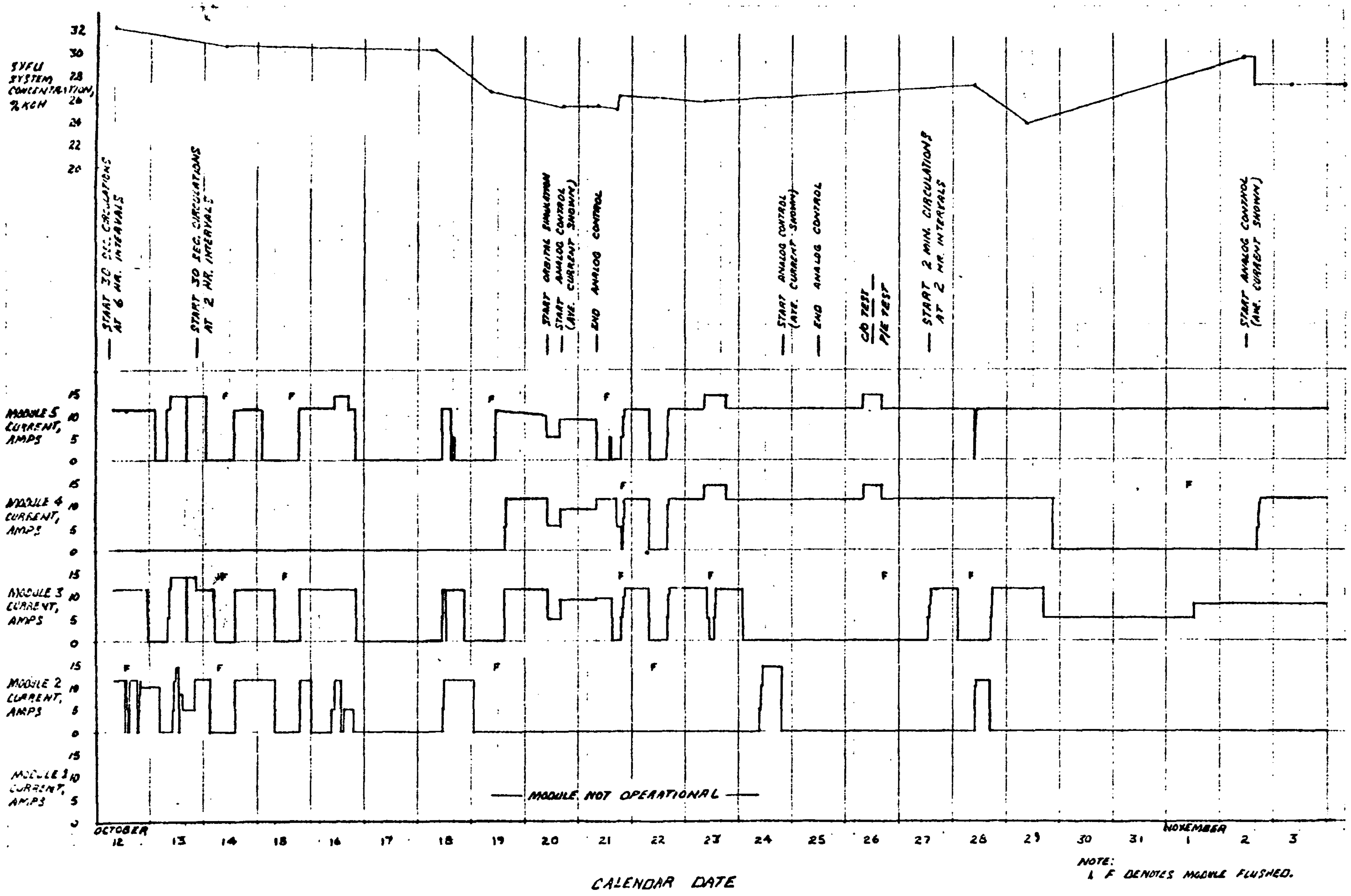


FIGURE 5-41 SVFU MODULE CUR[illegible]NT AND SYSTEM CONCENTRATION PROFILES

Specific module failures and shutdowns will be discussed in detail in paragraph 5.7.2. Figure 5-42 shows two system shutdowns. On 9 November the unit was shutdown automatically due to the Dymec recorder power plug being allowed to inadvertently work loose. The other shutdown occurred on 19 November when the technician employed an incorrect procedure during a magnetic tape change. The system was off approximately 5 seconds.

As shown on Figures 5-41 and 5-42 analog control of current was attempted. This proved to be very difficult to achieve as one module was operating at only 8 amperes and the module voltages for the other two modules varied so much that one module was only slightly affected by the analog control whereas the other module was greatly affected by the controller. Maintaining the desired 3 hour analog cycle was impossible as the needle valves used for bleed rate control were not sensitive enough to extend the cycle beyond 2-2 1/2 hours. It was decided that analog control would be tested again when 3 modules were operating at equal currents and near equal module voltages and the cycle would be adjusted to 2 hours.

On 26 November water was observed on the floor of the laboratory behind the unit. During a refill cycle water was observed escaping from the system through the accumulator nitrogen vent tube. It was apparent that the accumulator bladder had a hole in it. Normally the bladder exerts a 3.10×10^4 to 3.44×10^4 N/m^2 gage (4 1/2 to 5 psig) pressure on the liquid in the system but the hole reduced the effective pressure to about 1.72×10^4 N/m^2 gage (2 1/2 psig). Permission was granted to adjust the regulators to regain proper differentials between all working fluids. Even though the bladder had partially failed the system continued operating successfully. In order to minimize the quantity of water lost through the accumulator vent tube, the refill cycle was adjusted to once every 2 hours instead of once per hour. The 30-second water fill duration was retained. All water lost through the vent tube was collected and considered in the mass balance.

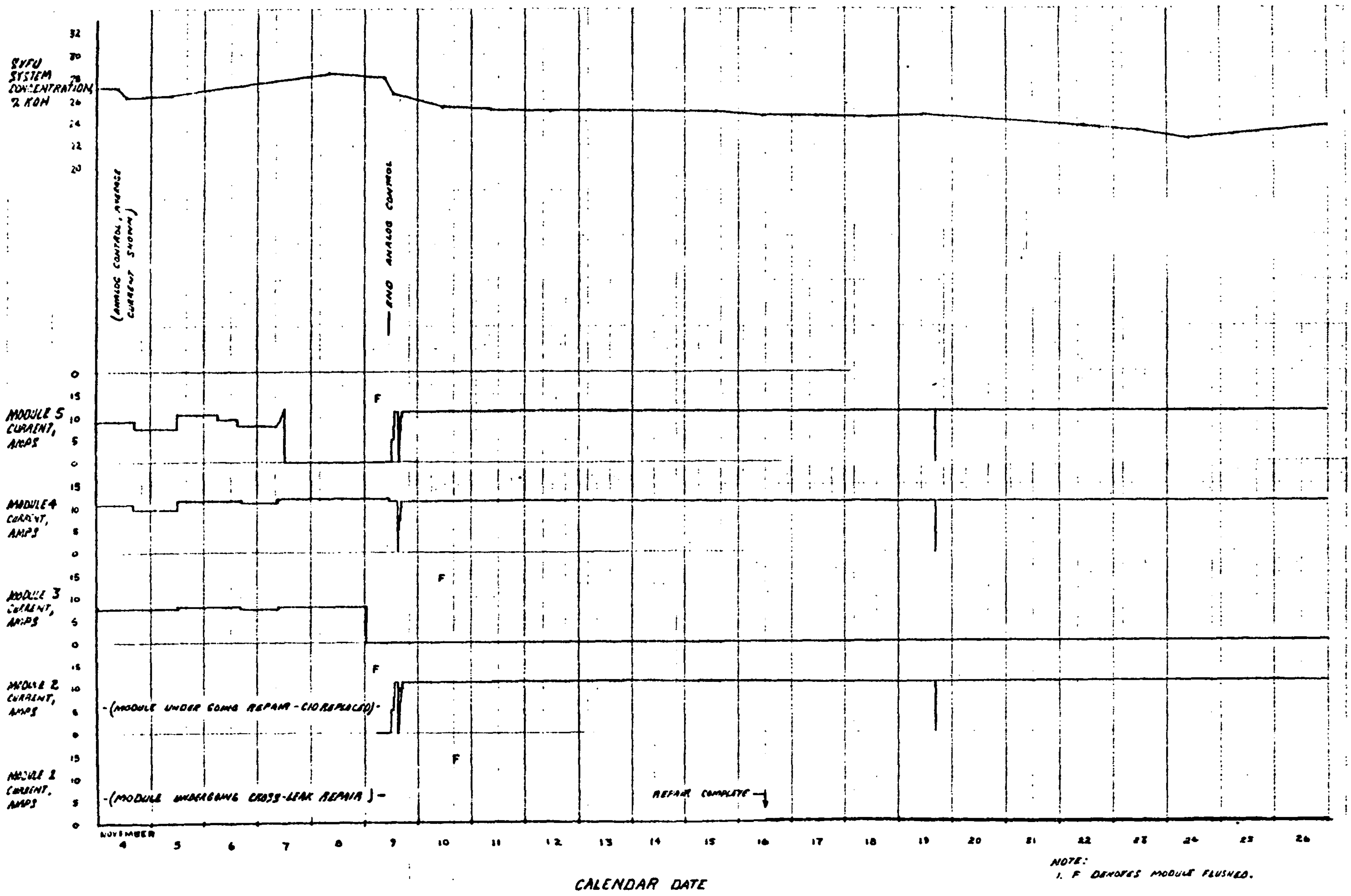


FIGURE 5-42 SVFU MODULE CURRENT AND SYSTEM CONCENTRATION PROFILES

Electrolyte concentration in the system was 26.5% on 9 November. The concentration gradually decreased to a low of 22.5% on 24 November. It may have gone lower but no measurements were taken between 24 and 29 November. The measurement on 29 November indicated a concentration of 24.4%. The increase was caused by a release of KOH by module 4 after the removal of the other two modules, that had failed on 28 and 29 November. The line on Figure 5-43 shows a gradual increase rather than the more probable rapid increase that occurred after the removal of two modules. It was postulated that the increase flow of electrolyte solution through module 4 during circulation caused a reversal of the KOH collection process thus allowing system KOH concentration to increase. The second cause of concentration decrease was due to seepage of KOH from the system on all modules and the 2-phase separator. After failure of modules 2 and 5, module 4 was continued in operation and observed for improvement in or continued degradation of performance. Some improvement was observed and it was decided to allow module 4 to continue operating alone.

Figure 5-43 shows the performance of the system for the period 27 November through 19 December 1971. The figure indicates that the electrolyte loop concentration was 25.3% on 30 November and gradually dropped to 22.6% on 8 December. Since module 4 was the only module operating and system leakage was low the KOH was apparently accumulating in the module. The concentration was increased to 26.1% on 16 December just prior to restarting the 3 modules. On 17 December the KOH concentration had dropped to 22.7% with very little external leakage. Again, it was evident that the modules were collecting KOH at an adverse rate.

As each module failed between 28 November and 8 December, the KOH external to the module and in the thermal box was collected and analyzed to determine total KOH lost from the system. The information is tabulated below:

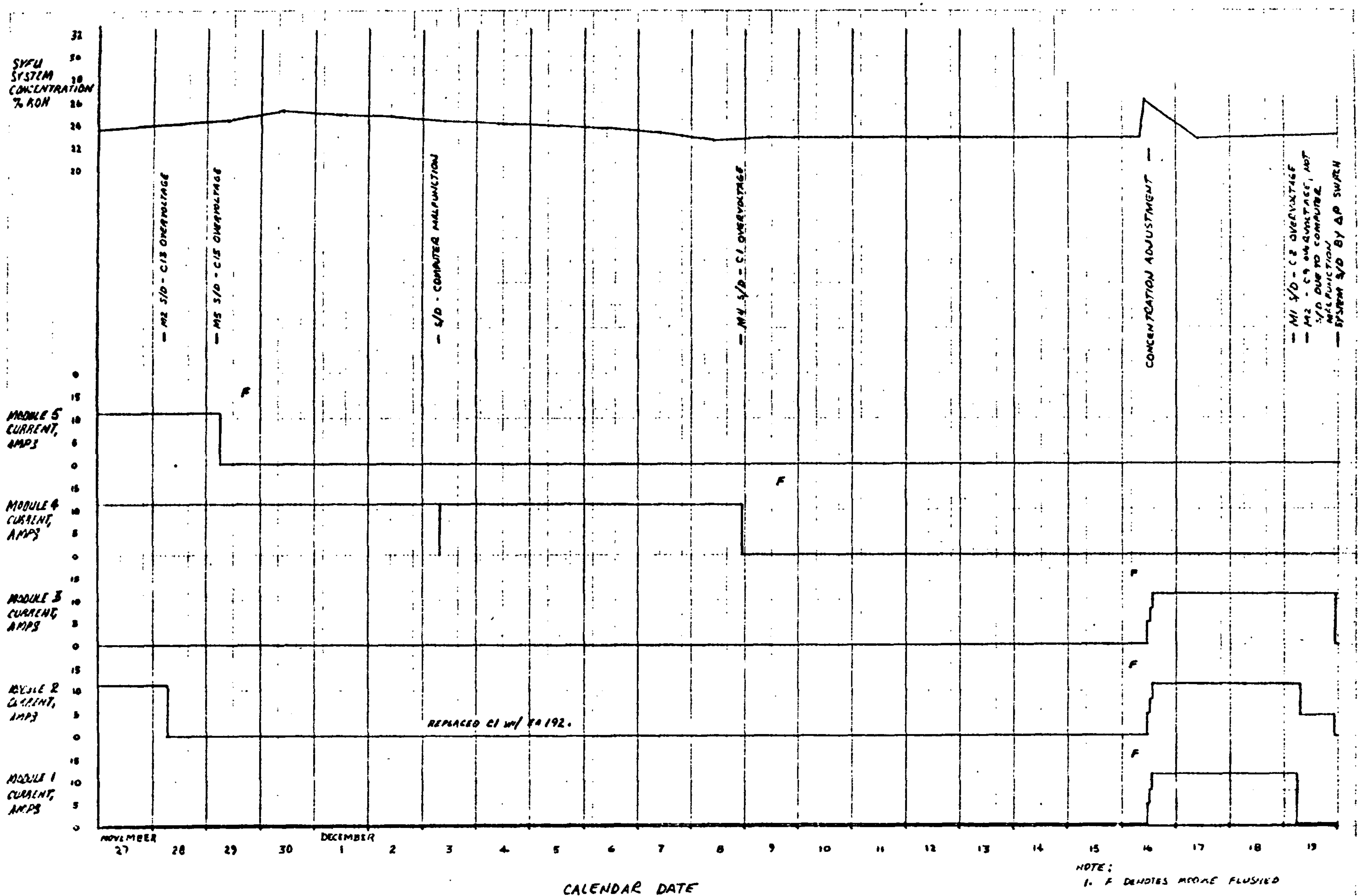


FIGURE 5-43 SVFU MODULE CURRENT AND SYSTEM CONCENTRATION PROFILES

Date	Module & Position	Total Material Removed (grams)	Concentration (% KOH)	KOH (grams)
30 Nov. '71	P2 - M2	10.7	39.3	4.2
	P3 - M5	6.9	45.8	3.2
9 Dec. '71	P1 - M4	82.4	45.6	37.6
	Separator	113.0	46.9	53.0

Analysis of available information on the performance of the modules up to this time indicated that the new 1970 configuration modules (numbered 4 and 5) were allowing salt bridging in the H_2 cavity under the conditions of operation used. At this time program direction was received to stop using the 1970 design modules, as the salt bridging effect was an undesirable condition not readily repeatable and definitely not something desired for space applications. Hence, modules 4 and 5 were set aside and only modules 1 through 3 were to be used.

On 9 December the water accumulator was removed from the system and replaced with a stainless steel and plastic unit containing a Bellofram bladder. The old unit was disassembled and several small holes were found in the bladder at the area adjacent to the end section at the shell weld bead. Some roughness could be felt in this area. Thus, the most probable reason for bladder failure was abrasion of the tube at the rough weld area.

After the system shutdown on 8 December, the separator was removed from the system and inspected and tested for leaks. All bolts were checked for breakaway torque. Instead of being the expected 7.90 to 8.46 Newton meters (70 to 75 inch pounds), the breakaway torque was between 3.95 and 6.20 N.m) (35 and 55 inch pounds). After retorquing to 8.46 N.m (75 inch pounds), the separator was pressurized with helium to 3.44×10^5 N/m^2 gage (50 psig). Leaks were observed at the quick disconnect (QD). All the o-rings in the 0.95 cm (3/8 in) diameter QD's were replaced. The o-rings on the 0.64 cm (1/4 in) QD's were in good condition. The separator was again pressurized with helium at 3.44×10^5 N/m^2 gage (50 psig) for 6 hours. The pressure decayed 1.52×10^4 N/m^2 gage (2.2 psig) in this period. This was considered acceptable. The separator continued to show leaks of KOH during the period of 16 December through 28 December and it was therefore decided to disassemble the separator. Visual inspection of each separator cell revealed that the cell heater wires were in contact with the KOH. Examination also showed many fine cracks running longitudinally in flow channels. It appeared that these cracks allowed KOH to reach the heater wires. Examination of unused condenser sections also showed similar cracks. It was thought that this could be a manufacturing anamoly common to all similar parts. Also, measurement of heater wire resistances indicated values, for all large separator cells, between 15,000 and 600,000 ohms. Review of the data sheets indicated that the separator temperature was reading 341°K (154°F) prior to 16 December, 338°K (149°F) between 16 and 24 December and 329°K (133°F) subsequent to 24 December indicating that some cell heaters had failed. Contact between the heater wires and the electrolyte may also have caused some stray electrolysis within the system. Review of the gas venting data did not reveal a particular time when the gas venting quantity changed significantly, although it was evident that when module 4 was operating in the system alone it gave off almost as much gas as when modules 1, 2 and 3 were operating together.

The electrolyte sample taken on 24 December showed the concentration had dropped to 24.5%. The next sample taken was on 29 December about 20 hours after the system had shutdown. This sample measured 22.1% KOH. The rate of change of the concentration between 24 and 25 December is not known. Figure 5-44 shows this data and problems encountered with modules 1, 2 and 3 between 20 December 1971 and 11 January 1972.

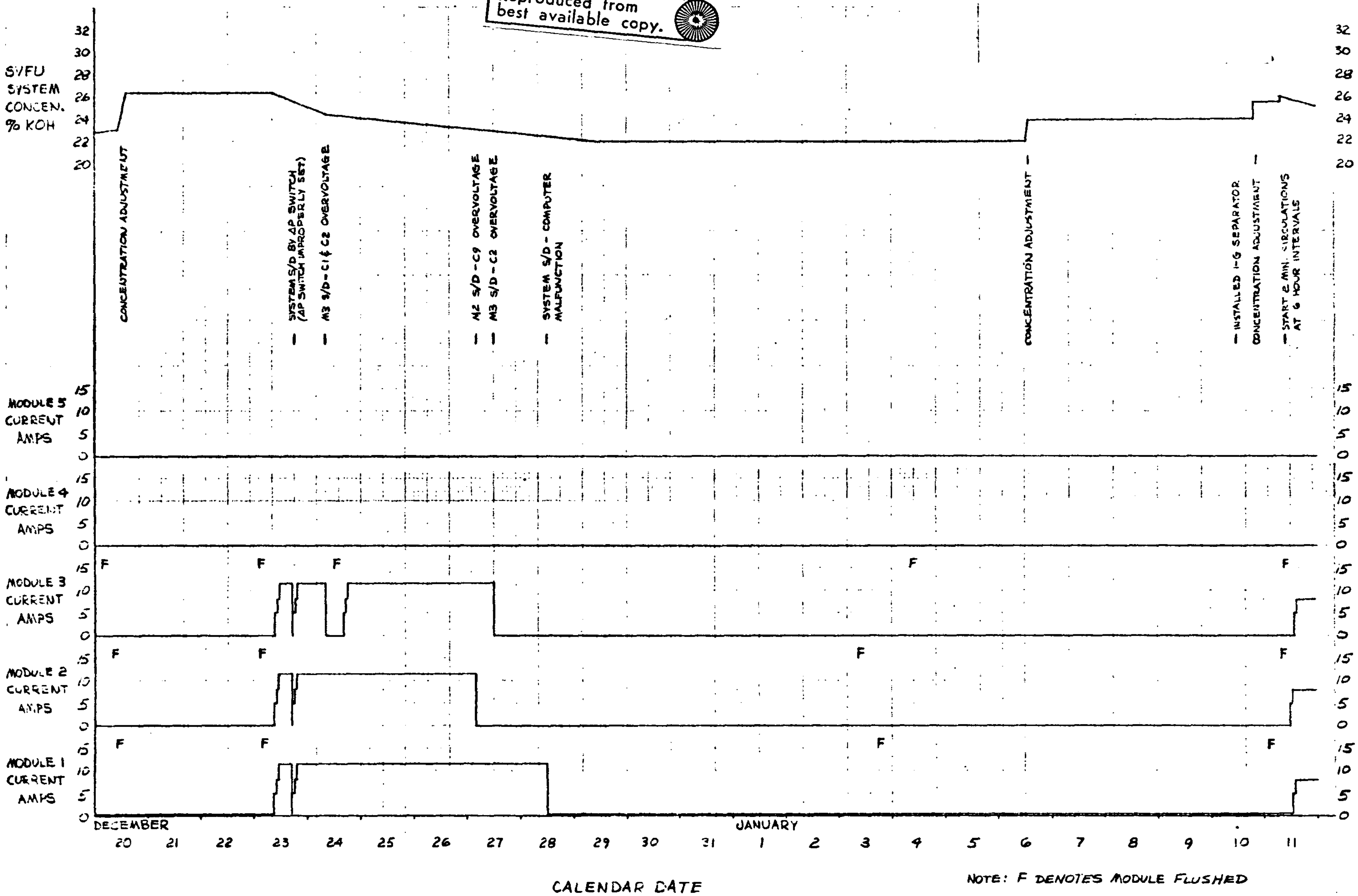


FIGURE 5-44 SVFU MODULE CURRENT AND SYSTEM CONCENTRATION PROFILES

The short term shutdown occurring on 23 December was caused by the differential pressure switch. While the system was down a check was made of all four switch settings. The low water switch setting was found to be approximately 2.55×10^4 N/m^2 differential (3.7 psid). This is 40% out of tolerance. The system normally operated with a hydrogen to water differential of 1.72×10^4 to 2.75×10^4 N/m^2 gage (2 1/2 to 4 psig). Therefore it is easy to see that the 2.55×10^4 N/m^2 differential (3.7 psid) could have been reached at any refill period where there was a momentary surge of the pressurization gas. Shutdowns due to differential pressure switches had all been occurring at the termination of the accumulator refills. The switch was reset at 4.13×10^4 N/m^2 differential (6 psid), the normal position. The system was not operated between 20 and 23 December in order to repair the crossleak in module 1. Finally, the non-operation after 28 December was due to the MDAC facility being closed for the holidays and the requirement for replacing the zero-g separator with a 1-g unit. The system was restarted on 11 January 1972.

The data of Figure 5-45 shows the period from 12 January to 3 February. The system shutdowns were just long enough to remove modules from the system, perform visual inspections, flush each cavity and then all cavities, install the module back in the system and restart. Some minor adjustments were made to the electrolyte circulation configuration. On 11 January the circulation pump operated 2 minutes every 6 hours with all the electrolyte flowing through one module. On 20 January the duration was increased to 10 minutes every 6 hours and on 26 January continuous circulation was employed with all fluid flowing through all modules simultaneously.

Three different electrolyte concentrations were tried. In all cases, the electrolyte and water matrices were charged with 30.0 to 30.5% KOH. The water cavity was charged with 26.0% on 11 January, 26.0% on 14 January, 22.9% on 20 January and 30.2% on 26 January. None of these changes seemed to produce an immediate long term improvement in performance. The test period terminating on 22 January, due to 115 vac circuit failure, showed

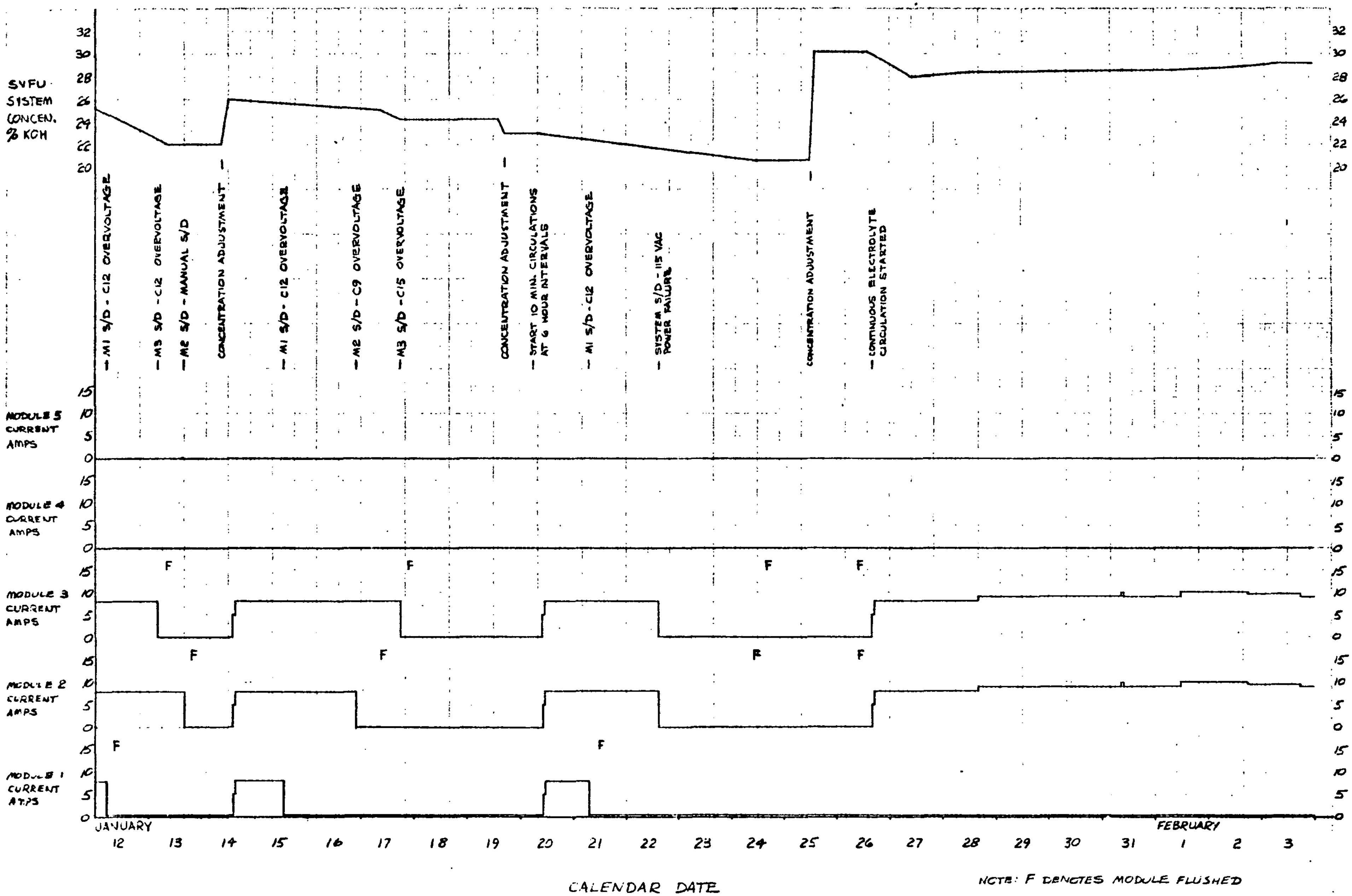


FIGURE 5-45 SVFU MODULE CURRENT AND SYSTEM CONCENTRATION PROFILES

the most promising operation, but the duration was not sufficiently long to draw meaningful conclusions. Continuous electrolyte circulation with an initial charge concentration of 30.2% KOH provided 9 days of continuous operation at reduced current levels. Figure 5-45 shows the attempts to increase current. Each time the current was increased a few cell voltages would climb up to 1.68 volts. At that point the current was reduced by 0.5 amperes. The first attempt at 10 amperes on 31 January was terminated after only 2 hours because of the rapid rise of cell voltages at the relatively low operating temperatures employed. After that attempt the operating temperature of the system was increased to about 352°K (174°F). A marked improvement in system performance was noted. After 24 hours of steady state operation the current level was again increased to 10 amperes. A gradual increase in all voltage was noted. The increase in voltage level was slow enough to permit the unit to operate at 10 amperes for about 30 hours before reaching the 1.68 cell volt limit.

A pump problem arose during the first attempt to operate with the new separator. The pump would come on and operate for about 30 seconds and then stop pumping even though the pump motor was still operating. The problem was solved by reducing slightly the temperature of the electrolyte in the separator. It appeared that the sudden change in temperature within the pump was causing thermal gradients that were binding up the pump after about 30 seconds of operation. After shutting the pump off for about 30 second to 1 minute and then restarting manually the pump would run normally. Also a boiling phenomena was encountered in the pump due to high temperature and low pressure at the pump gears. Reducing the separator temperature about 5°K (9°F) eliminated the problem.

The check valve on the electrolyte discharge line from module number 1 was checked on 21 January and was found to leak slowly but steadily when provided with less than 30.5 cm (1 foot) of water head. This is approximately the head the check valve was subjected to in the system. Any head greater than 30.5 cm (one foot) caused the check valve to seat properly and not leak. About 15 tests were performed with slightly differing head pressures and check valve positions. Twelve tests resulted in leaks, usually when the head was less than 30.5 cm (1 foot) and the check valve was oriented on a horizontal position as it is in the system. On 24 January modules 2 and 3 were also checked for back leakage through the check valves. The results were the same as for module 1, slow but steady leakage. This appeared to be part of the cause of KOH accumulations within the cells. A modification to the system was made whereby the check valves were replaced with two-way solenoid valves. The valves were actuated open when the circulating pump was actuated, and closed when the pump was stopped. This provided more positive isolation of the cells from KOH between pump circulations.

The chain-of-events shutdown on 22 January, caused by the loss of the 115 volt AC power source, indicated the need to rearrange the AC power for each electrolysis system and the signal conditioning console. As a result each electrolysis unit and the signal conditioning console was placed on separate AC circuits. The loss of one electrolysis unit would not affect the other equipment. However, loss of the signal conditioning console would still cause shutdown of the SVFU as a fail-safe measure.

Two basically different modes of operation are shown on Figure 5-46; continuous electrolyte circulation and intermittent circulation (2 minutes every 6 hours with all flow through 1 module). The intermittent electrolyte circulation was done only after the addition of the new isolation solenoid valves to the outlet manifold. The valves were installed on 21 February. Both conditions showed improvement in module performance. Three different electrolyte concentrations were also employed. The first condition employed 30.2% KOH in all cell cavities and in the electrolyte loop. This worked quite well and allowed performance for 10 to 10 1/2 days before shutdown on 5 February. Unfortunately the failure was caused by the circulating pump progressively failing and not by the cells failing. When the pump stopped circulating the electrolyte, the front end plate thermocouple (TC1) indicated excess temperature and the computer shut the modules off. Exactly why the temperature went up so

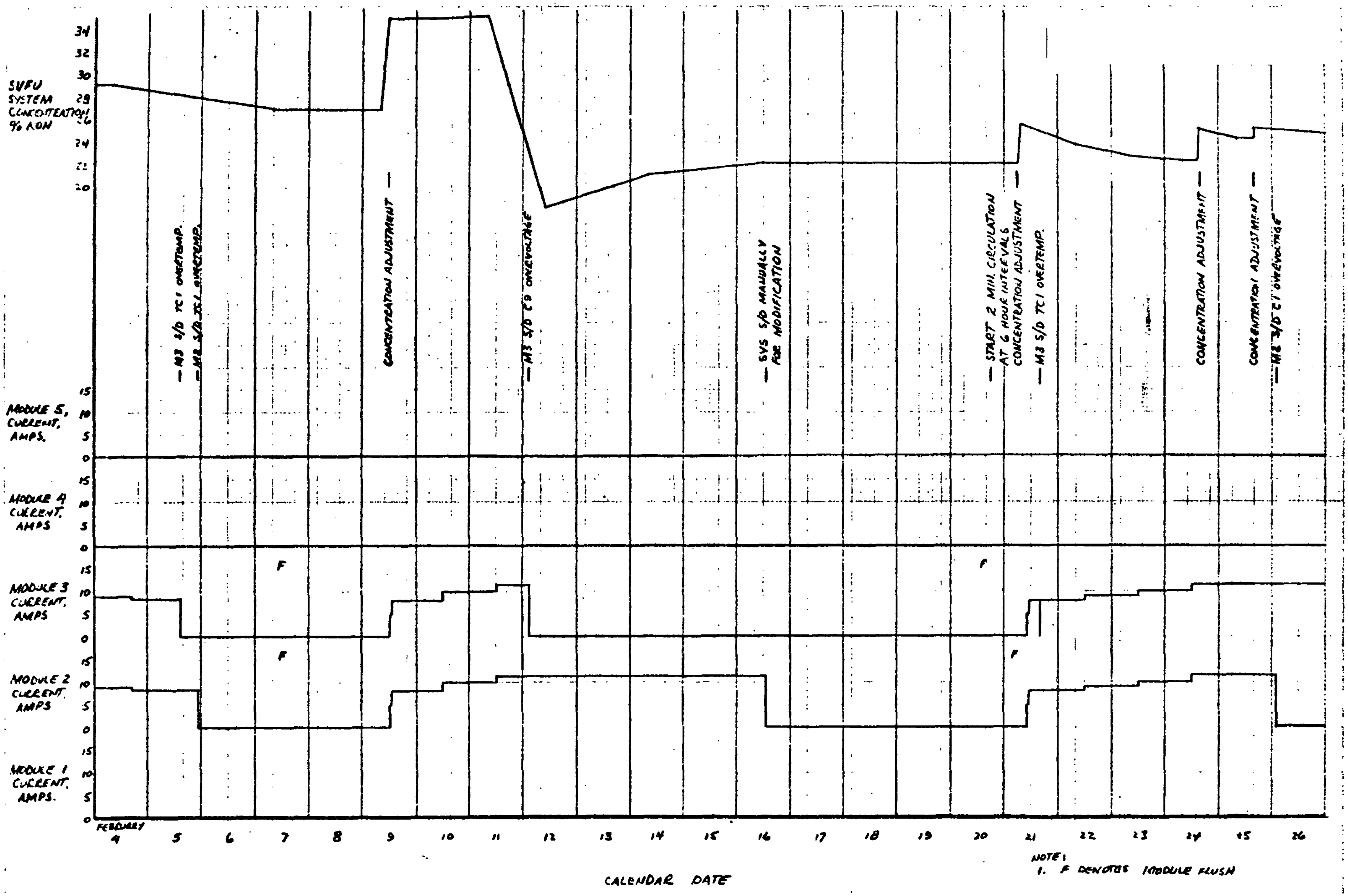


FIGURE 5-46 SVFU MODULE CURRENT AND SYSTEM CONCENTRATION PROFILES

drastically is not fully understood. At the time the modules were shutdown all parameters within the modules were indicating normal conditions except TC1. Module voltages had been increasing over a 3-day period and to prolong the operation module current was being decreased at the rate of 0.5 amps per day. (See 4-5 February on Figures 5-72 and 5-108.)

After this shutdown the modules were cleaned up and restarted. This time the concentration was adjusted to the condition specified by the module manufacturer. The 35% KOH concentration was used in all cavities and in the continuously circulating electrolyte loop. After 2 1/2 days of operation module 3 shutdown for high cell voltage in cell 9. The failure analysis was compounded by a large leak in module 3. Electrolyte concentration decreased from 35% to 18.2% in approximately 24 hours. Module 2, which continued to operate, did not show any excess flooding. The loop concentration gradually increased to 22% over the next four days due to the mixing of high concentration electrolyte from the vent trap. On 16 February module 2 was shutdown manually to add solenoid valves to the module electrolyte discharge line to provide positive isolation of modules against KOH migration when the circulating pump was not operating.

On 21 February the system was restarted with the cell cavities at a concentration of 30.0 to 30.5% KOH and the electrolyte loop at a concentration of 25.6% KOH. Module 3 operated about 6 hours at which time it shutdown due to overtemperature in TC1. This was found to be caused by the temperature controller needle sticking which caused the cell heater to stay on too long. The temperature controller was freed up and the module was restarted. Module 2 developed a leak which caused the system concentration to drop to 22.4%. An adjustment was made on 24 February and again on 25 February in an attempt to replace the amount of KOH lost from the system due to the leak. Finally on 26 February module 2 failed due to cell 1 going out of tolerance on cell voltage.

The pump failure on 5 February was caused by the driven magnet within the pump rubbing against the seal cup. Inspection of the two o-rings that hold the magnet in aligment on the driven shaft indicated that the o-rings were damaged and not holding the magnet properly on the shaft. With new o-rings the pump worked very well.

Two basically different modes of operation were performed during the period shown on Figure 5-47; distilled water feed at the bottom of the module (normal mode) and water feed at the top of the module. The object of top feed was to eliminate the effect of electrolyte maldistribution, due to specific gravity differences, in cell 15 of the module. Unfortunately this latter solution was not very satisfactory. Module voltages increased rapidly and finally stabilized for a few days of operation at a level much higher than the bottom feed mode. This effect was thought to be due to restricted water feed caused by gas accumulation in the upper manifolds and turnaround plate of the modules. When the modules were returned to normal bottom feed, cell 15 was disconnected electrically and thus the cell was used as a liquid bypass line. This also did not prove beneficial, as cell 14 reacted with high cell voltages even faster than cell 15 did originally. All testing accomplished during the period 27 February to 12 April used the same electrolyte concentrations; that is, 30.0 to 30.5% KOH in the electrolyte and water matrices and 26.5 ± 0.5% KOH in the water cavity and circulation loop. It is evident from the figures that without external leaks and with positive isolation of the modules from the circulating loop, the system KOH concentration stayed relatively constant.

Figure 5-48 and 5-49 show the final operating conditions employed, these included 14 and 15 cell operation, circulations of 2 minutes duration at 2 hour intervals and 6 hour intervals and 30 seconds duration at 40 minute intervals, and electrolyte concentration of 30.0 to 30.5% in the matrices with 26.0 ± .5% in the circulating loop and 35% in the matrices with 32% in the circulating loop. The 30 second duration circulation at 40 minute

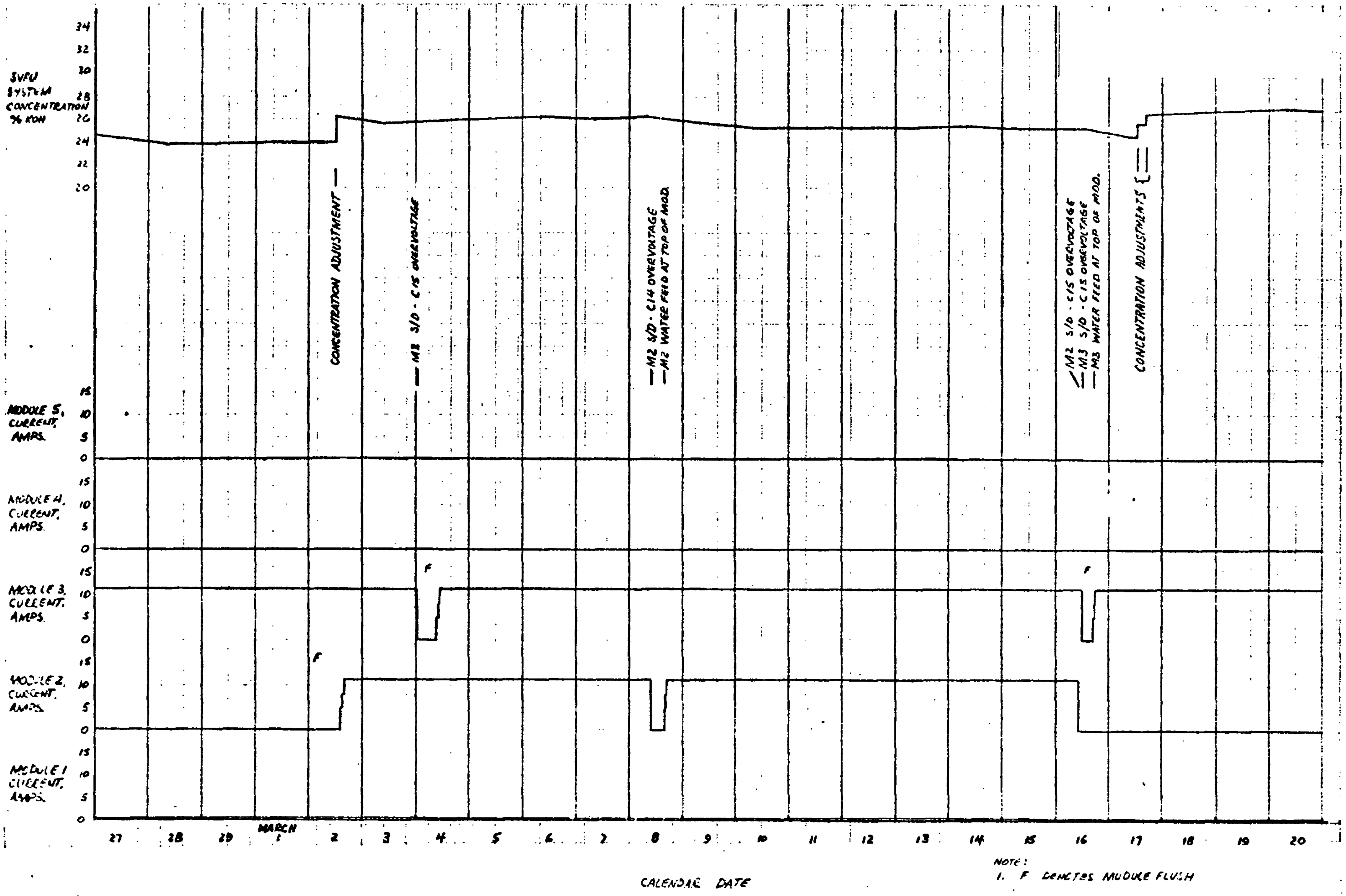
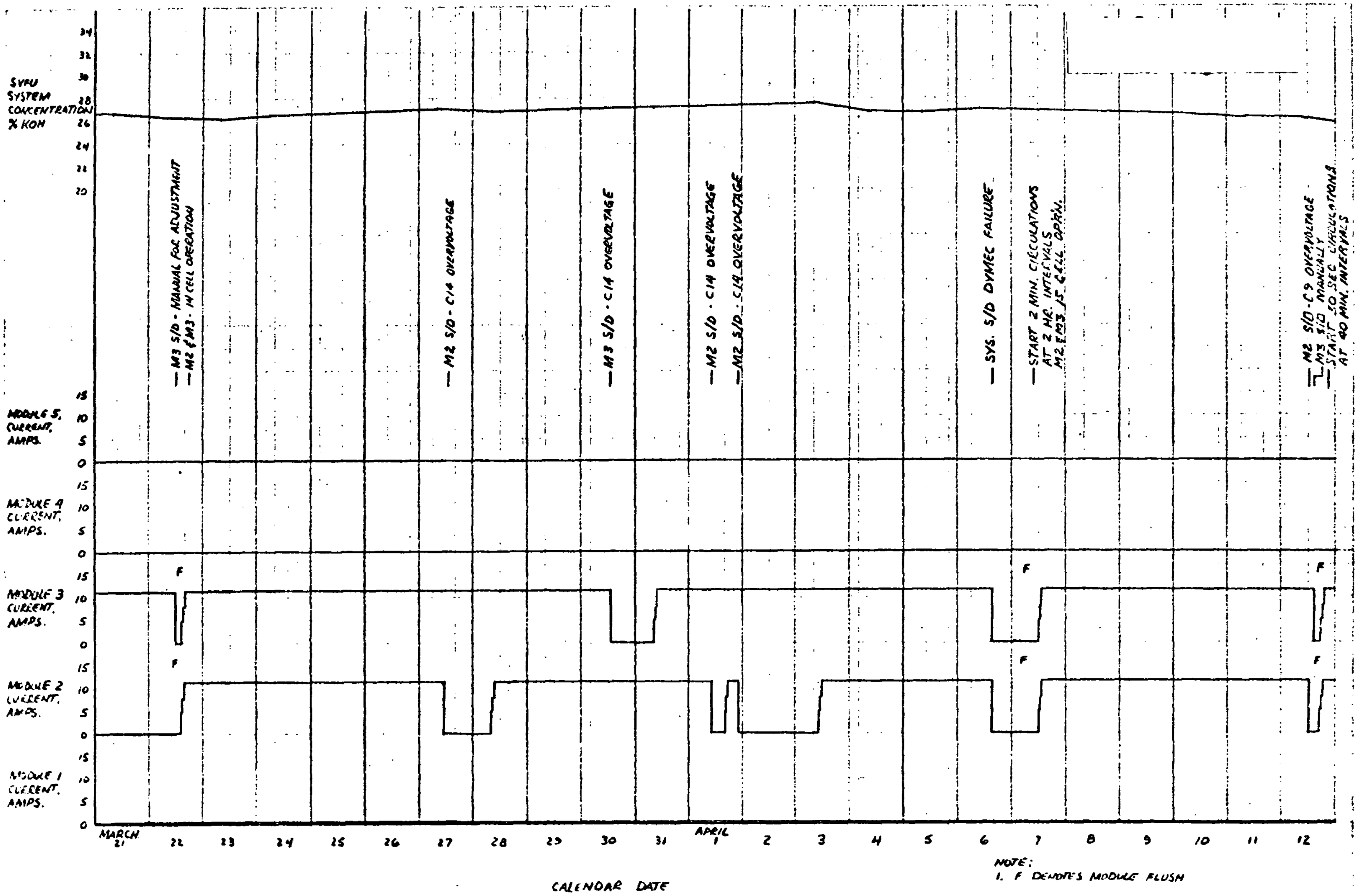
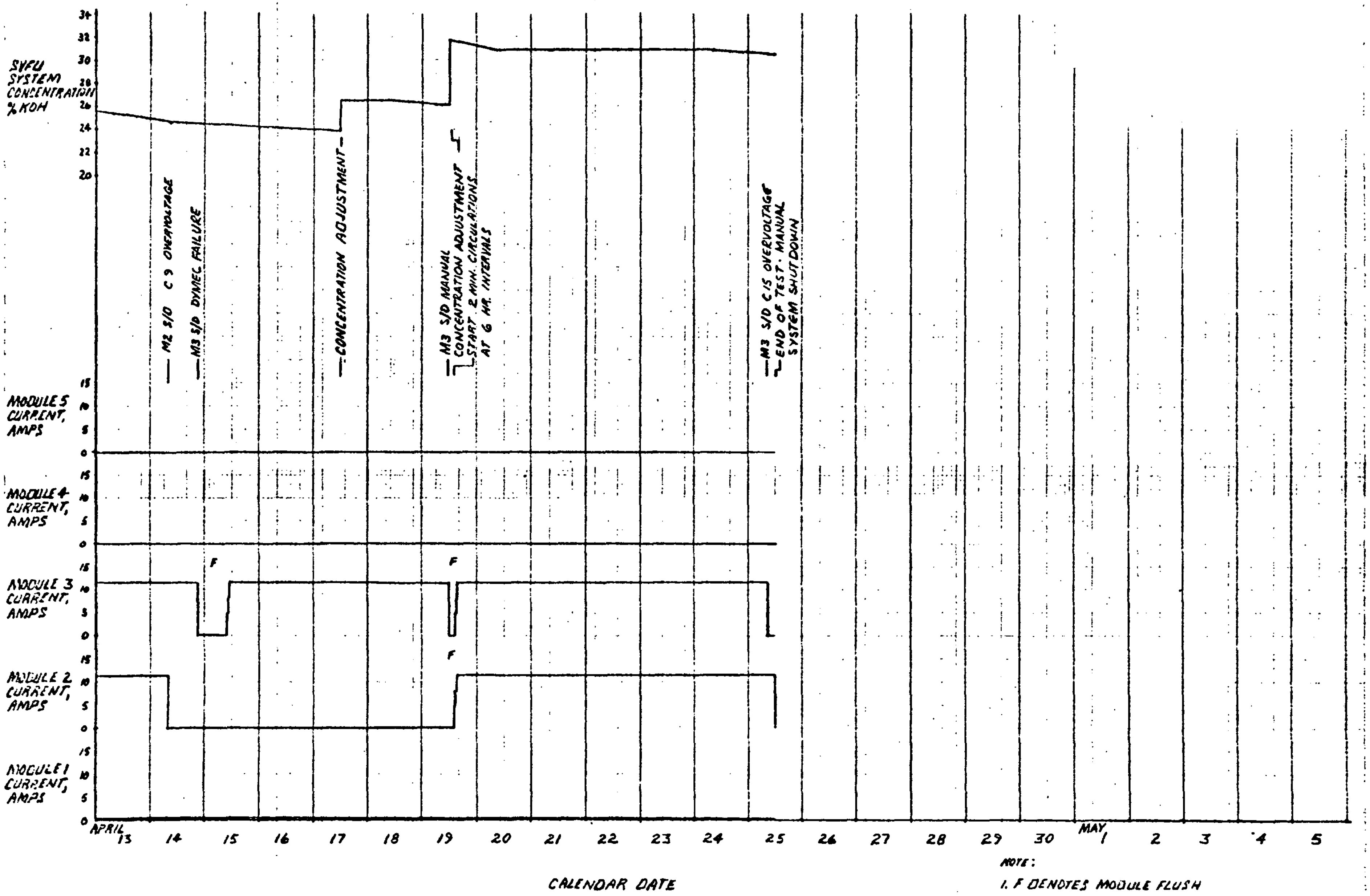


FIGURE 5-47 SVFU MODULE CURRENT AND SYSTEM CONCENTRATION PROFILES



NOTE:
1. F DENOTES MODULE FLUSH

FIGURE 5-48 SVFU MODULE CURRENT AND SYSTEM CONCENTRATION PROFILES



NOTE:
1. F DENOTES MODULE FLUSH

FIGURE 5-49 SVFU MODULE CURRENT AND SYSTEM CONCENTRATION PROFILES

intervals was an attempt to duplicate the operation experienced during the 100-hour checkout test. The results were not identical because during the 100-hour test makeup feed water was supplied to the separator and was mixed with KOH before being admitted to the modules. The water was supplied directly to the module in the endurance test, hence, the effect of different specific gravity liquids was still experienced to some extent in cell 15. Operation at higher concentrations was an attempt to offset the KOH washout effect occurring in cell 15. This change was not any more beneficial than any other change, however, cell voltages of other cells in the module did appear to be more stable at the higher concentration. The test program was terminated before complete and repetitive results could be obtained. The figures also show that when no leaks occur in the modules the electrolyte concentration remains fairly constant and very little electrolyte migration takes place. The major problem encountered in this testing that appeared to prevent long term operation was the maldistribution of electrolyte in cell 15 of the modules. Longer duration operation should be obtained if the water feed mode or feed location were changed to eliminate the effect of different specific gravities. Intermittent circulation should be retained to minimize parasitic power requirements.

Figure 5-50 shows the scheduled and actual O_2 production during the test period. The decrease in production rate on the SVFU after day 88 was a direct result of the decision to operate the unit on only the 1968 modules. The unit was able to maintain required production rates of 3.63 Kg/day (8 lb/day) for only 2 days with 3 module operation. During all other periods the modules were: a) operating at reduced capacity, b) experiencing malfunctions, c) being troubleshot to detect problems, d) undergoing 1/2 day operation (day 1 and 183), and e) shutdown. Operation of orbital simulation was not conducted on this unit. Analog control of system current was conducted with limited success during test days 8 through 15. Success was limited because of electrolyte maldistribution problems and the modules were not all operating at uniform conditions. Operation at 14 amperes was not attempted due to the limited time the modules would operate at 11.3 amperes before shutdown due to high cell voltages from electrolyte maldistribution.

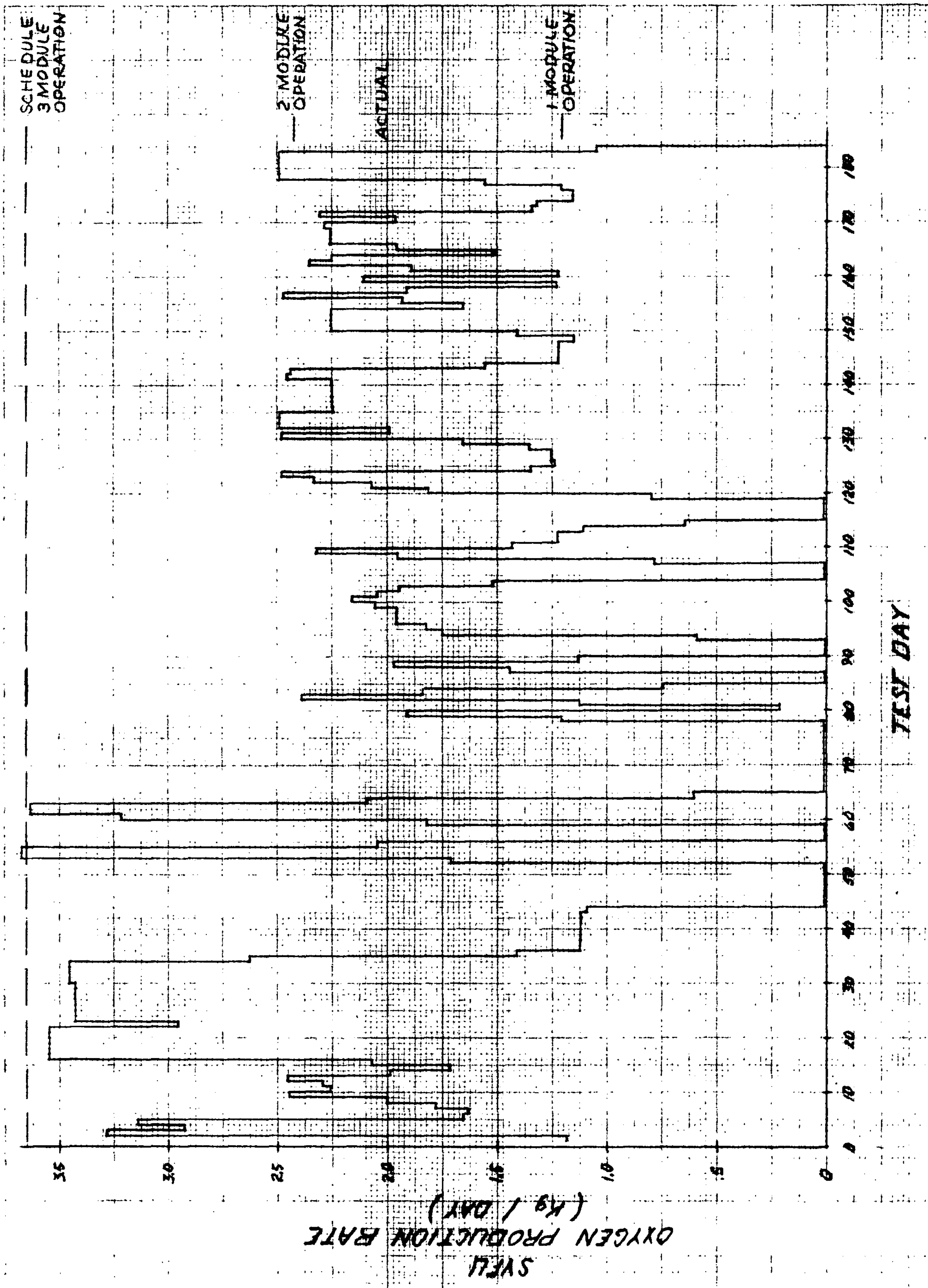


FIGURE 5-50 OXYGEN PRODUCTION RATE COMPARISON

Figure 5-51 shows the ideal cumulative module test time and the actual test time in terms of module hours. Cumulative operating time closely followed scheduled operating time early in the program when 3 modules operated almost continuously for 20 days. It is important to note that the amount of down time experienced by both units was considerably larger than one would expect with around-the-clock attendance and the provisioning of ample spare parts. Because of the development nature of this program, the effort was generally limited to 40-hour weeks and only limited spare parts provisioning.

5.7.2 Module Performance

This section describes the performance of each module during the course of the 26-weeks of testing.

5.7.2.1 Module 1

This module was not used in the 80-hour checkout test nor in the early weeks of testing due to a suspected cross leak in one of the cells. The crossleak would occur whenever the H_2 to H_2O differential pressure exceeded 2.76×10^4 N/m^2 (4 psi). No leak was evident at a 2.31×10^4 N/m^2 (3.5 psi) differential. The module was disassembled and each cell checked separately. No crossleaks could be found. The module was reassembled and checked again - still zero leaks. Apparently the high flow and multiple flushing at 345°K (160°F) resulted in complete wetting of all matrices thus eliminating the crossleak.

This module was first operated in the system from 1130 16 December through 0551 19 December 1971. It was shutoff by the computer because of overvoltage in cell number 2. The module was isolated from the circulations at 0730 on 19 December. Thus, the module experienced only one circulation prior to isolation. The module was physically removed from the system on 20 December, at which time all cavities were drained of liquid and the samples analyzed for KOH concentration. Results are as follows:

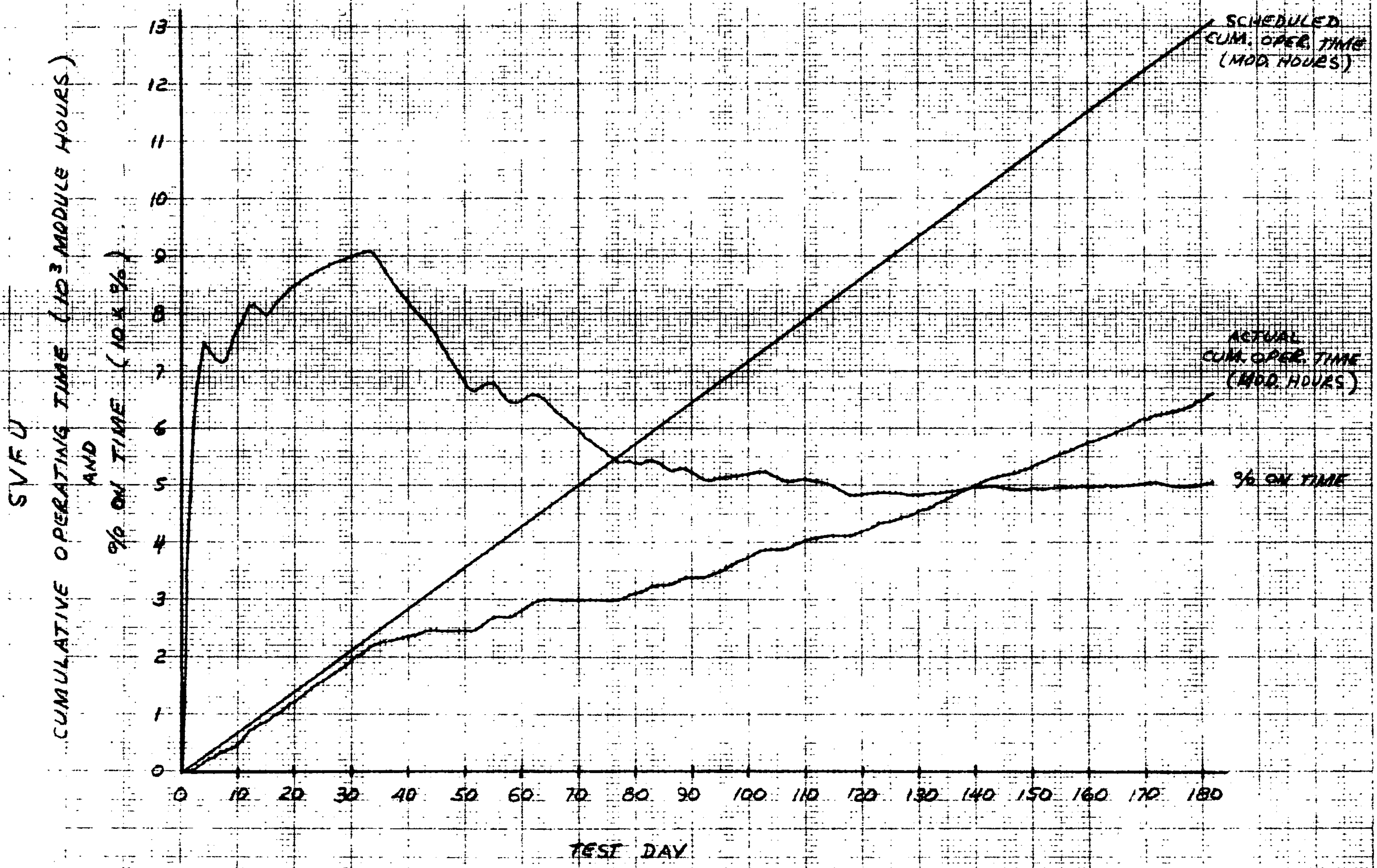


FIGURE 5-51 SYSTEM OPERATING TIME COMPARISON

H_2O Cavity	113 cc's	26.6% KOH
H_2 Cavity	2.4 cc's	33.6% KOH
O_2 Cavity	< 1 cc	Insufficient sample

Electrolyte loop concentration at this time was 23.4%. The module cell cavities were drained after removal from the system to determine how much liquid existed in each cavity and if any significant KOH buildup existed. During peroper operation there should be zero liquid in the H_2 and O_2 cavities. The concentration of the liquid in the water cavity should be equal to the loop concentration just after a circulation. This value should increase slightly over the next 30 minutes and then remain relatively constant until the next circulation. Figures 5-52 and 5-53 show the performance conditions of the module before and at the time of failure. The module was disassembled due to having observed large quantities of gas being discharged from the module during operation and during electrolyte circulation periods. Review of the hourly printout showed cell 12 with an unusually high cell voltage shortly after startup. It was thought that this cell could contain the crossleak. Cell 12 checked out in good condition, cell 13 and 14 checked out good. Cell 15 was discovered to have a cross leak at the water inlet manifold. The cross leak seemed to be around the water matrix and through the perforated sheet into the water inlet manifold. Pressure decay was 4 minutes from 3.44×10^4 N/m^2 gage to 1.39×10^4 N/m^2 gage (5 psig to 2 psig), no leak or pressure decay occurred with pressure differential less than 1.39×10^4 N/m^2 gage (2 psig).

FIGURE 5-52 PERFORMANCE HISTORY (POSITION 1- MODULE 1)

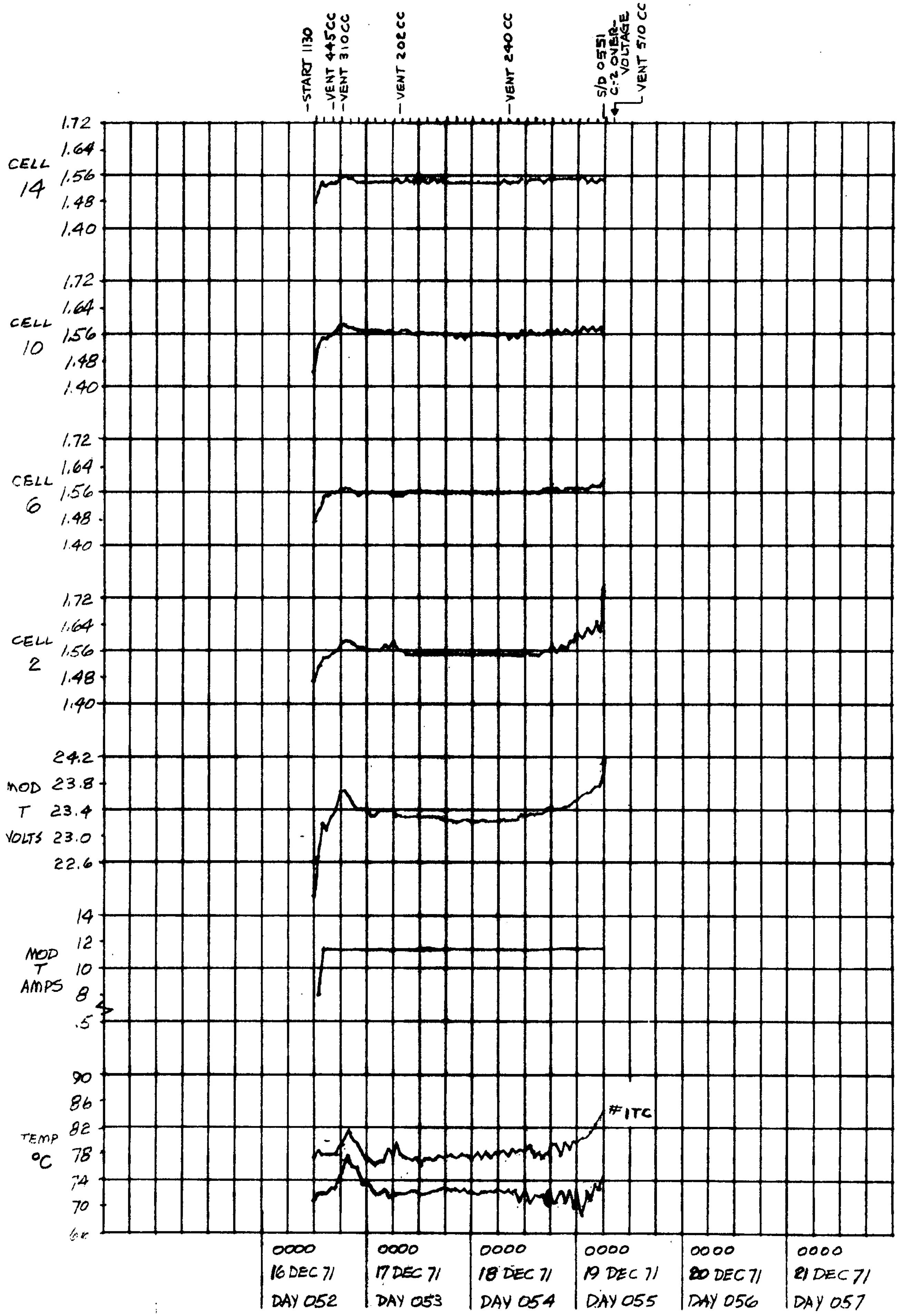
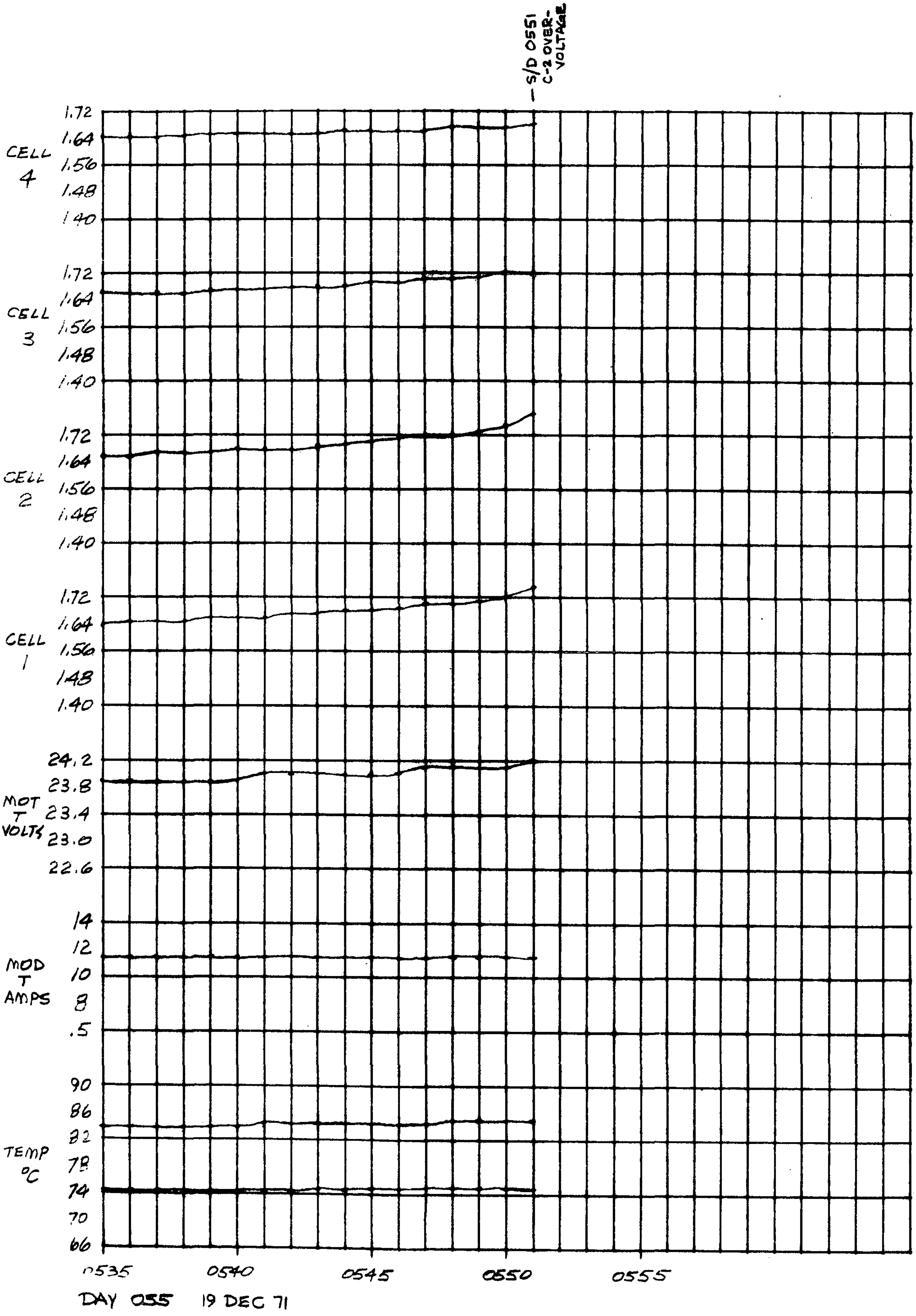


FIGURE 5-53 PERFORMANCE HISTORY (POSITION 1-MODULE 1)

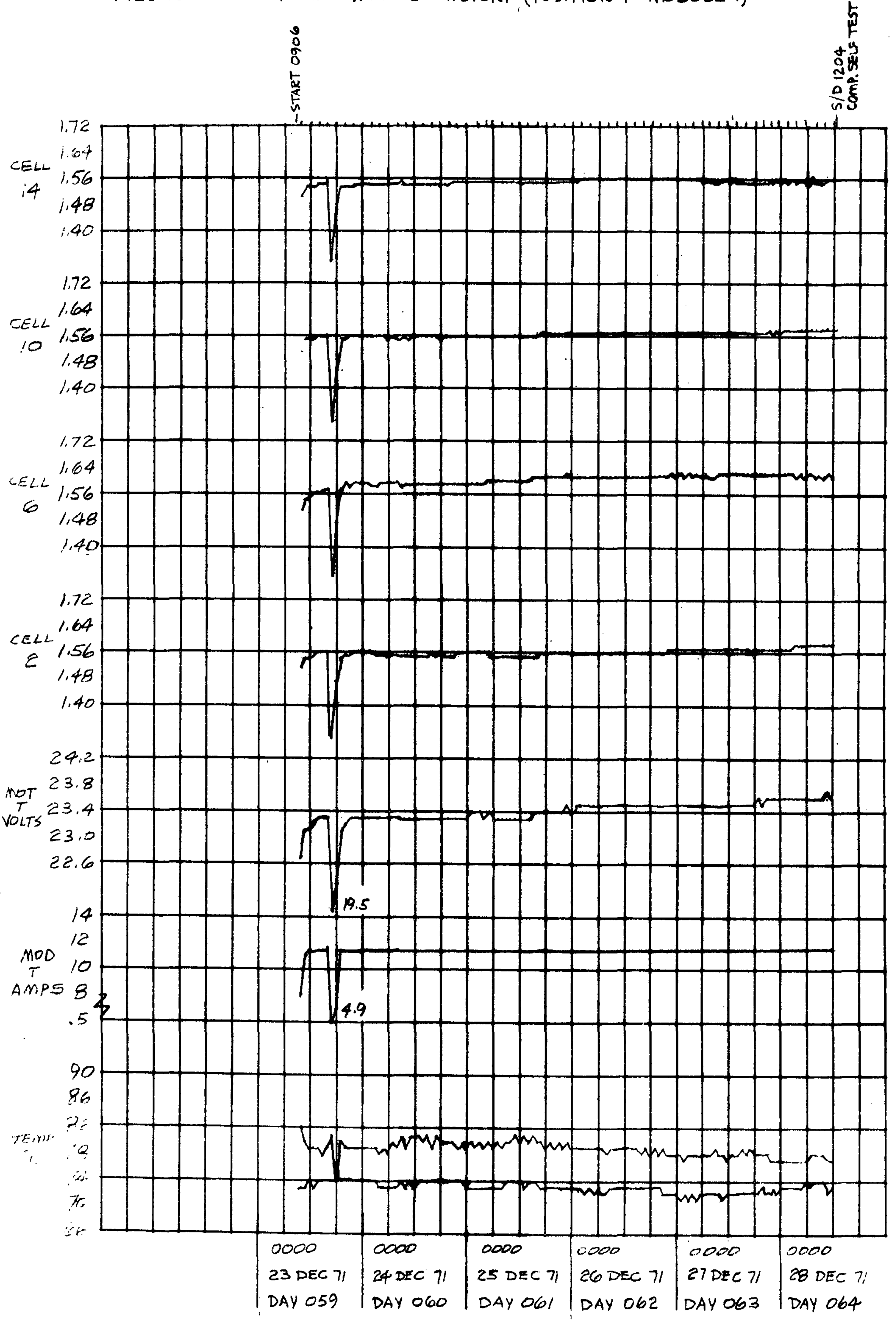


A spare cell was located to replace the malfunctioning cell. This spare cell was placed in position 15. The spare cell had no thermocouple. This was not expected to affect cell operation in any way. Module 1 was reassembled and leak checked. When all leaks had been properly sealed and the module checked out on all tests, the module was reinstalled in the system in preparation for restart on 23 December. The shutdown shown on Figure 5-54 at 1446 on 23 December was a total system shutdown due to a differential pressure switch being improperly set. Module 1 operated from 1750 23 December to 1204 28 December 1971 at which time the computer shut the total system down. Module 1 was operating at very uniform conditions with proper cell voltages at the time of shutdown. This is shown on Figure 5-54. Module 1 was removed from the system at 0830 on 29 December. All cavities were drained and the samples analyzed. The results are shown below. Also shown are the initial and final flush cart concentrations, after separately flushing each cavity of the module:

Cavity	Liquid Sample	Concentration	Flush Cart Concentration Initial	Flush Cart Concentration Final
H_2O	136 cc's	25.2%	30.3%	30.0%
H_2	38 cc's	25.2%	30.0%	29.7%
O_2	zero liquid	-----	29.7%	30.2%

Flush cart concentration measurements were made to determine if any KOH buildup existed within the module matrices. A 0.2% change in the KOH concentration in the flush cart liquid represented a significant KOH buildup in the cell matrices. The flush cart normally contains 2 to 4 liters of solution. Conversely, a decrease in KOH concentration in the flush cart indicated the cell matrices had been subjected to a significant loss of KOH. The implication of this data is that the module H_2O and H_2 cavities equalized during the 20 hours following module shutdown and preceding sample taking. Also with no pressure differential between cavities, flooding of the O_2 cavity did not occur. Thus the flush cart showed a statistically significant concentration change only when flushing the O_2 cavity. After 4 1/2 days of operation the module voltage had increased from 23.3 to 23.7 volts. The module was inspected and found to have very little external KOH and was considered ready for reuse in the system after being reflushed with the proper concentration electrolyte.

FIGURE 5-54 PERFORMANCE HISTORY (POSITION 1 - MODULE 1)



Each of the next 3 times the module operated it would operate about 20 hours and then cell 12 would go out of tolerance and the module would be shutdown. The first period was from 1328 on 11 January to 0448 on 12 January. This was the period of time that the circulation pump was operating only 30 to 50 seconds before declutching. The module was removed from the system and placed on the flush cart. Initial concentration in the flush cart was 30.3% KOH. After one hour of flushing, the concentration in the flush cart was up to 32.9% KOH. It was felt at that time that the problem of excess KOH was caused by insufficient circulation. The module was carefully inspected for problems and found to be all right.

The module was reflushed to a 30.2% KOH concentration and reinstalled in the system at 1345 on 14 January. This time the module operated until 1257 on 15 January. The module cavities are drained on 17 January and the samples analyzed. The results are as follows:

H_2O Cavity	135 cc's liquid	22.7% KOH
H_2 Cavity	zero liquid	- - - -
O_2 Cavity	41 cc's liquid	24.0% KOH

The long interval between module shutdown and cavity draining reduces the value of the information obtained. Some flooding of the O_2 cavity did occur and a loss of KOH had occurred in the water matrix. This was further verified by the results of the cavity flushing. The flush cart concentration decreased from 31.0% KOH to 29.3% KOH after about 1 hour of flushing. The module was carefully inspected. Minor seepage was evident at the H_2 outlet fitting, between cells 11 and 12, at cell 15 and on the H_2O inlet fitting. All seepage was sufficiently small that disassembly was not warranted. The module was reflushed and made ready for its next attempt for successful operation.

The module was installed in the system and started at 0951 on 20 January and operated until 0742 on 21 January. Immediately after shutdown the module was removed from the system and all cavities drained and the samples analyzed. The results are as follows:

H_2O cavity	146 cc liquid	41.0% KOH

O_2 and H_2 cavities had zero liquid

The system electrolyte loop was 22.2% KOH at this time. After 3 hours with the H_2O cavity on the flush cart the concentration in the cart increased from 30.2% KOH to 31.6% KOH. The high concentration of the water cavity fluid and the fact that the module had not received a circulation for nearly 6 hours implied that KOH must have been leaking into the cells from either the solenoid valve or the check valve. The solenoid valve showed zero leakage but the check valve, as was stated earlier, demonstrated slow but steady leakage when minimum liquid head was placed on the valve in a reverse direction.

During an external leak check of the module excessive leakage was noted between cells 11 and 12. It was decided to disassemble the module and repair the leak. Careful inspection of each cell revealed that 6 cells in the module had hairline cracks in the heater wire sheet and in the water cavity cover sheet. These cracks allowed liquid to seep from the water manifold in each cell to the outside diameter of the o-ring groove and then out to the ambient from between the cells. The cracks were very small and could only be seen under a microscope or under water when the gas bubbles were visibly moving through the crack. The cracks were located in the thinnest and shortest length between the water cavity manifold and the exterior. This may be evidence of fatigue in the cells as a result of frequent compression/expansion during assembly and disassembly and during heating and cooling of operation.

Figures 5-55 and 5-56 shows the specific performance of module 1 during these three periods. No adequate explanation has been found as to why cell 12 went overvoltage each time a shutdown occurred, when all other cells were so much lower in cell voltage. After the 20 January failure, this module was considered a spare in the sense that good cells would be borrowed from the module to repair and replace malfunctioning cells in modules 2 and 3.

At the end of the test period about 9 cells had been repaired from the damaged cells of module 1. Repairing the cells was accomplished by testing each cell individually between plexiglas end plates. The assembly was pressurized to 34.4×10^4 N/m^2 gage (50 psig) and submerged in a tank of water. The origin of the bubbles was identified and the cell removed. Next the area was inspected for cracks, delaminations, and poor o-ring grooves. The areas requiring repairs were cleaned, scraped, and opened to allow patching or filling (depending on the size of the damaged area). Repairs usually required some ethylene dichloride as a solvent to fill the crack. When the solvent was dry, a KOH-compatible epoxy ("All Bond" made by ALLACO Products Inc. of Braintree, Mass.) was used to fill the remainder of the cut-back area. This procedure proved to be the most successful of all techniques tried. After repairs were made the cells were again tested individually to check the effectiveness of the repair. If the cell passed the leak test and electrical checks it was added to the stack of cells making up available spares. When 3 or more cells were available they were tested together. Finally the short stack was tested collectively with all the available cells.

Most of the damage found in the leaking cells was between the water cavity and the o-ring groove or between the water cavity and the cell heater. One case provided a number of hairline cracks that allowed KOH to seep into the outer periphery of the o-ring groove and then back out between the cells. The other case allowed the KOH to come in contact with the heater wire thus causing stray electrolysis within the cell and excess gas within the electrolyte circulation loop. The size and number of cracks governed the ability to repair the cell.

FIGURE 5-55 PERFORMANCE HISTORY (POSITION 1 - MODULE 1)

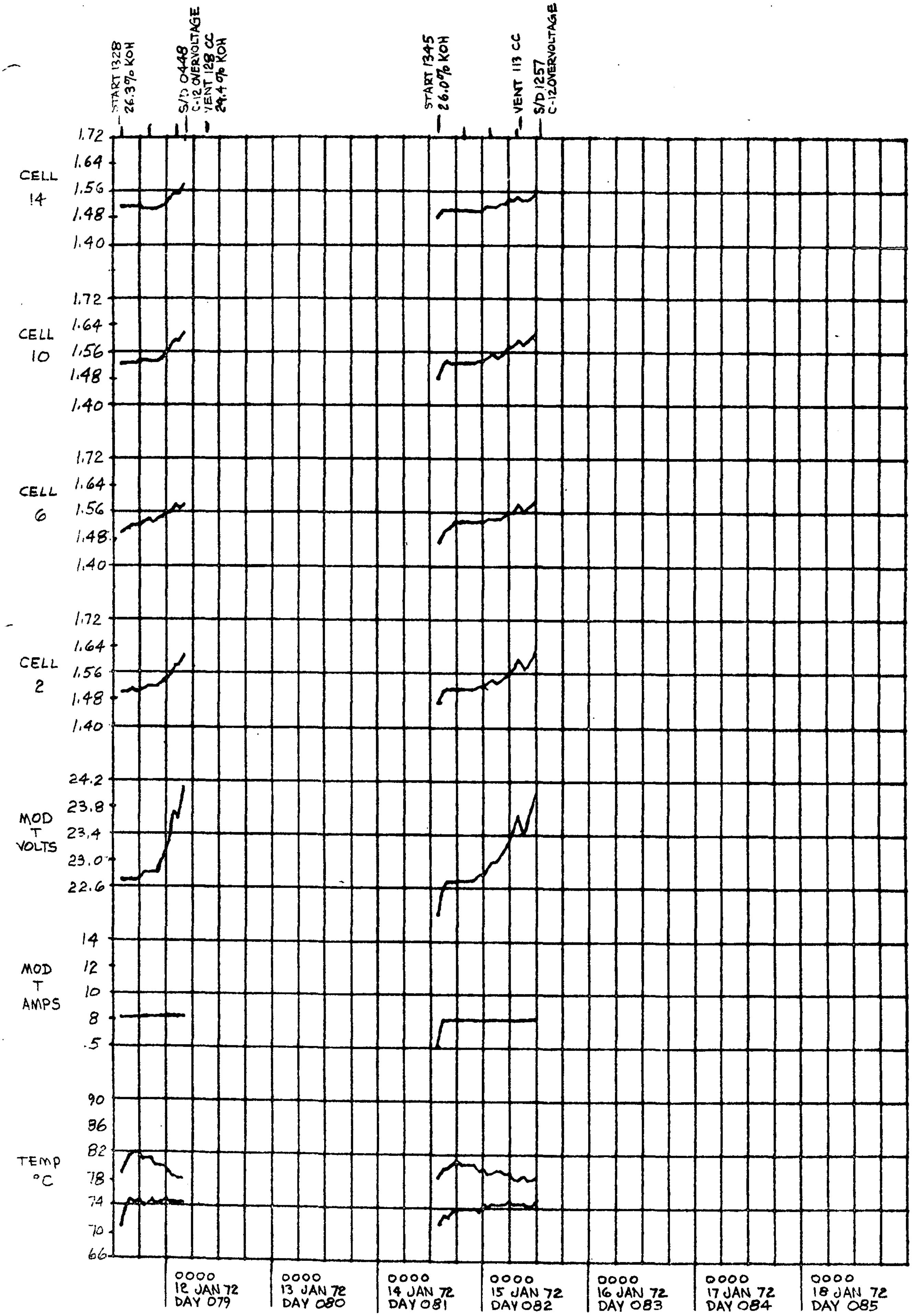
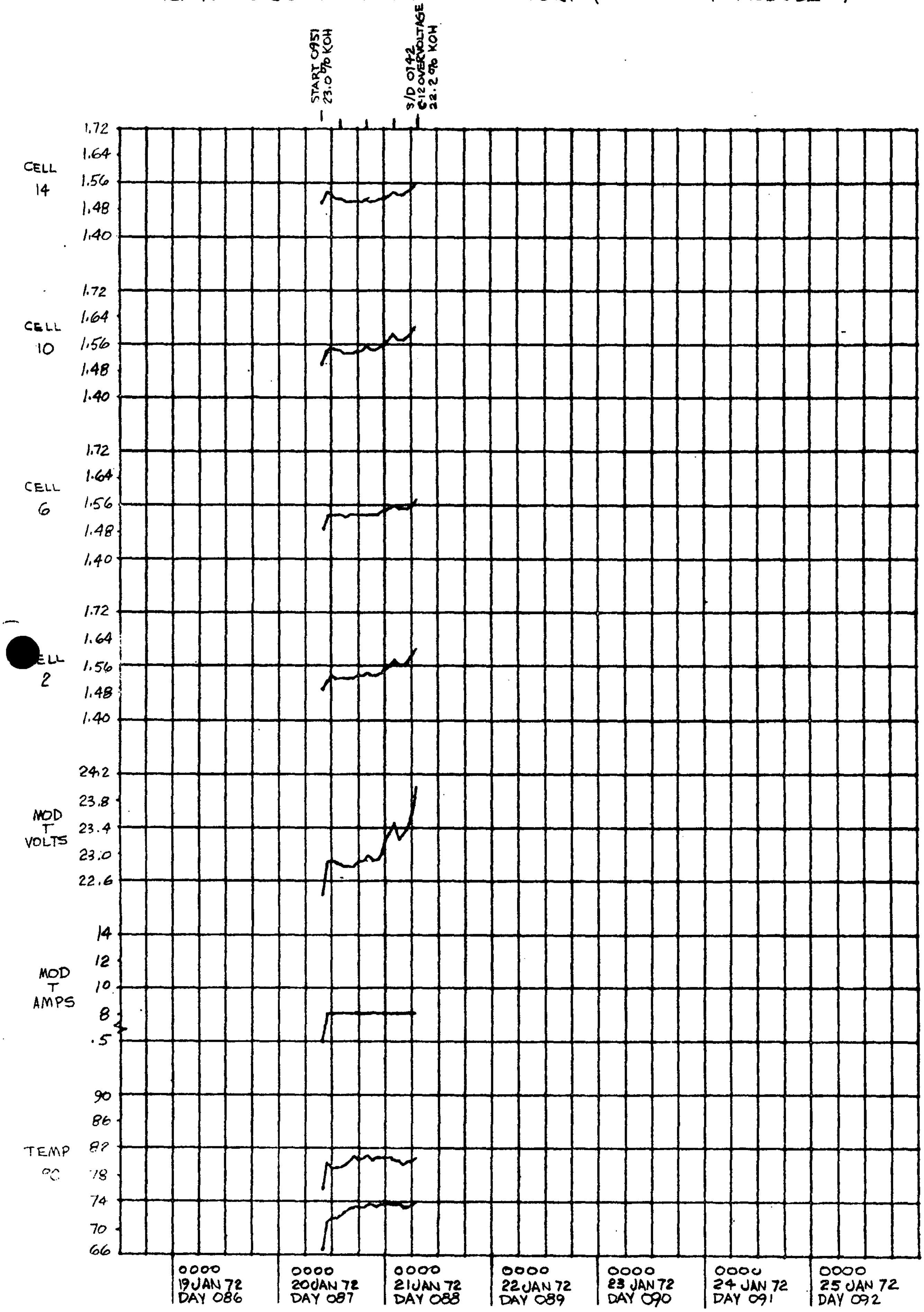


FIGURE 5-56 PERFORMANCE HISTORY (POSITION 1- MODULE 1)



5.7.2.2 Module 2

Figure 5-57 shows the first data plotted on the module. The period indicated is the latter part of the 80-hour checkout test. Figure 5-58 shows the performance in the first part of the performance testing. Both operating times lasted less than 10 hours and in both cases cell 10 caused the shutdown due to overvoltage. A review of the LSI data did not indicate any problem with cell 10. However, it was decided to replace cell 10 with a less sensitive spare cell.

The module was reinstalled in the system on 9 November and operated nearly continuously until 0613 on 28 November 1971, an operating period of almost 19 days (450 hours). Only one shutdown occurred. This was caused by human error while changing the Dymec tape and did not have anything to do with module performance. Review of Figures 5-59 through 5-61 indicates that cell and module voltage increased very slowly throughout the 19 day period. At 0613 on 28 November cell 13 went out of tolerance at 1.75 volts. The major peaks at 0900 on 11 November were caused by a manual circulation following immediately after an automatic circulation. This was necessary to collect a KOH sample. Due to this rather adverse effect the procedure was changed to allow venting the separator after the 0840 automatic circulation and taking the KOH sample after the 1040 automatic circulation. The rise in temperature on 17 November is not understood. No known changes occurred that could cause the effect. The smoother temperature curve after 1200 on 22 November was obtained as a result of shifting the automatic circulation periods. Circulations were changed to occur at 10 minutes after the even hours instead of 40 minutes after the hour. Visual inspection of the module after failure on 29 November indicated small leaks at cells 1 and 6. Bolt torques on this module were between 7.33 and 8.45 N.m (65 and 75 inch-pounds). The concentration of electrolyte in the flush cart dropped 3% during the first hour of flushing this module and then remained relatively constant. A pressure check of the module indicated a leak in cell number 1 at the thermocouple wire location. The leak necessitated disassembly of the module. Spare cell number EA-192 was installed in position 1 of this

FIGURE 5-57 PERFORMANCE HISTORY (POSITION 2- MODULE 2)

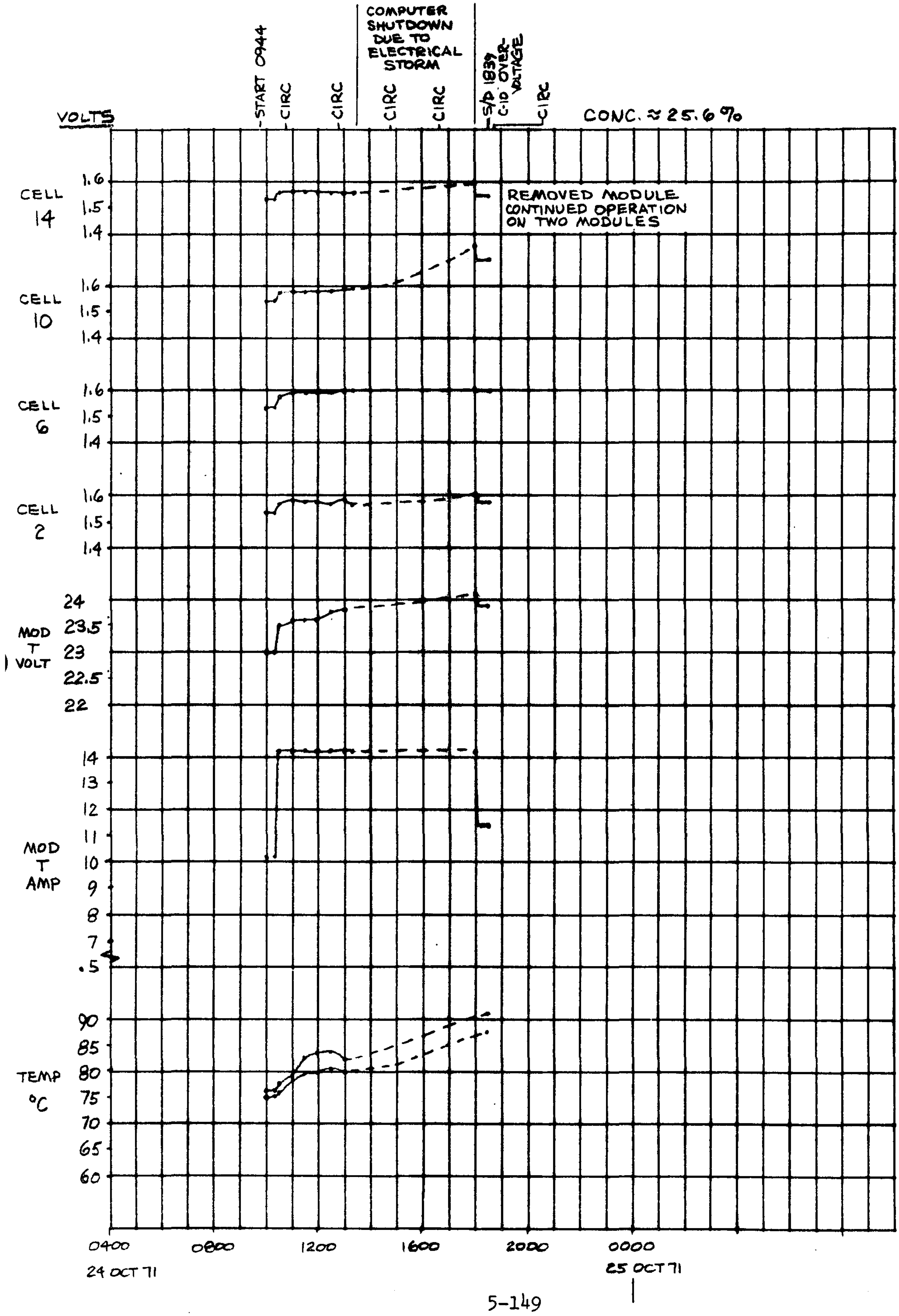


FIGURE 5-58 PERFORMANCE HISTORY (POSITION 3 - MODULE 2)

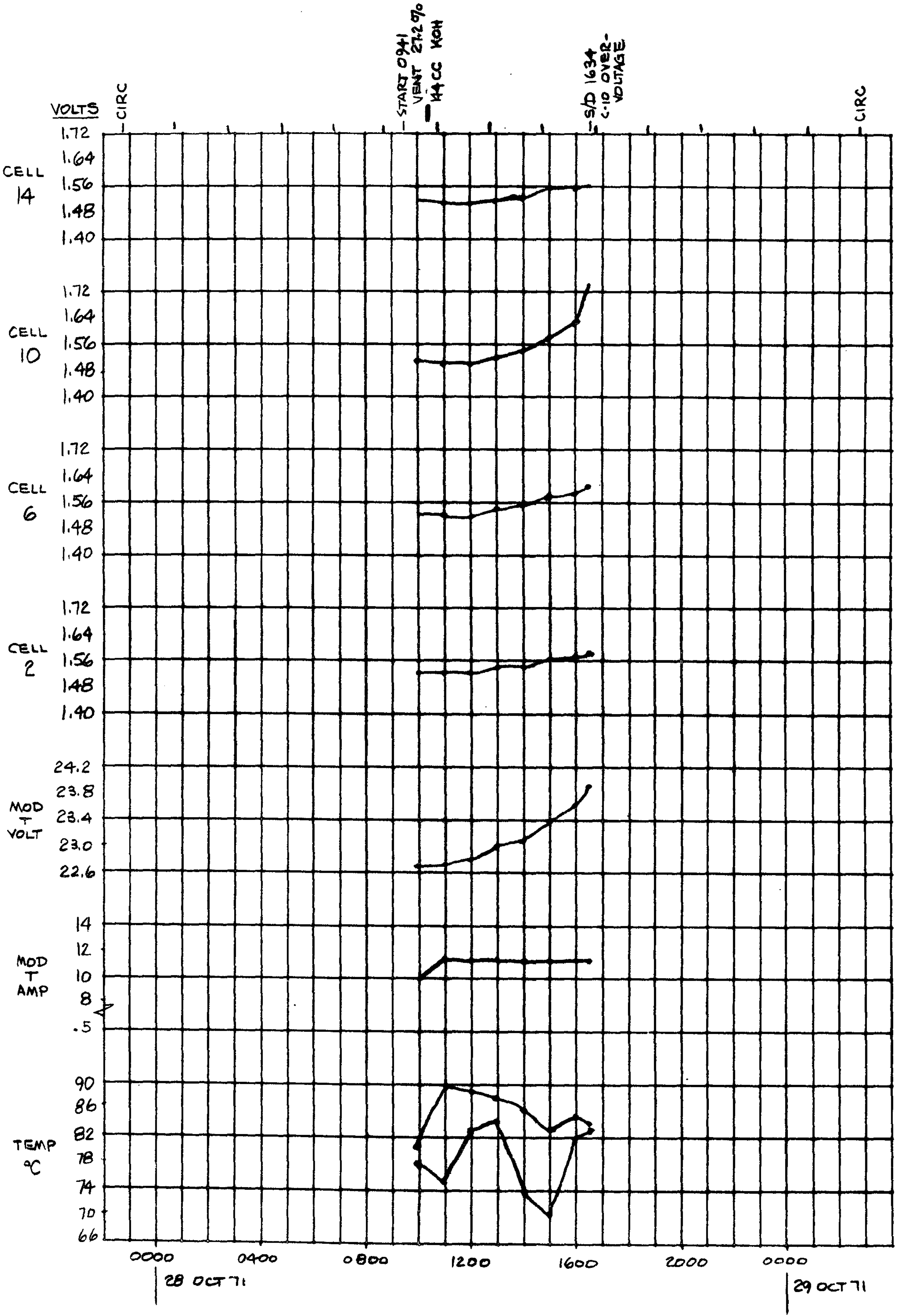


FIGURE 5-59 PERFORMANCE HISTORY (POSITION 2 - MODULE 2)

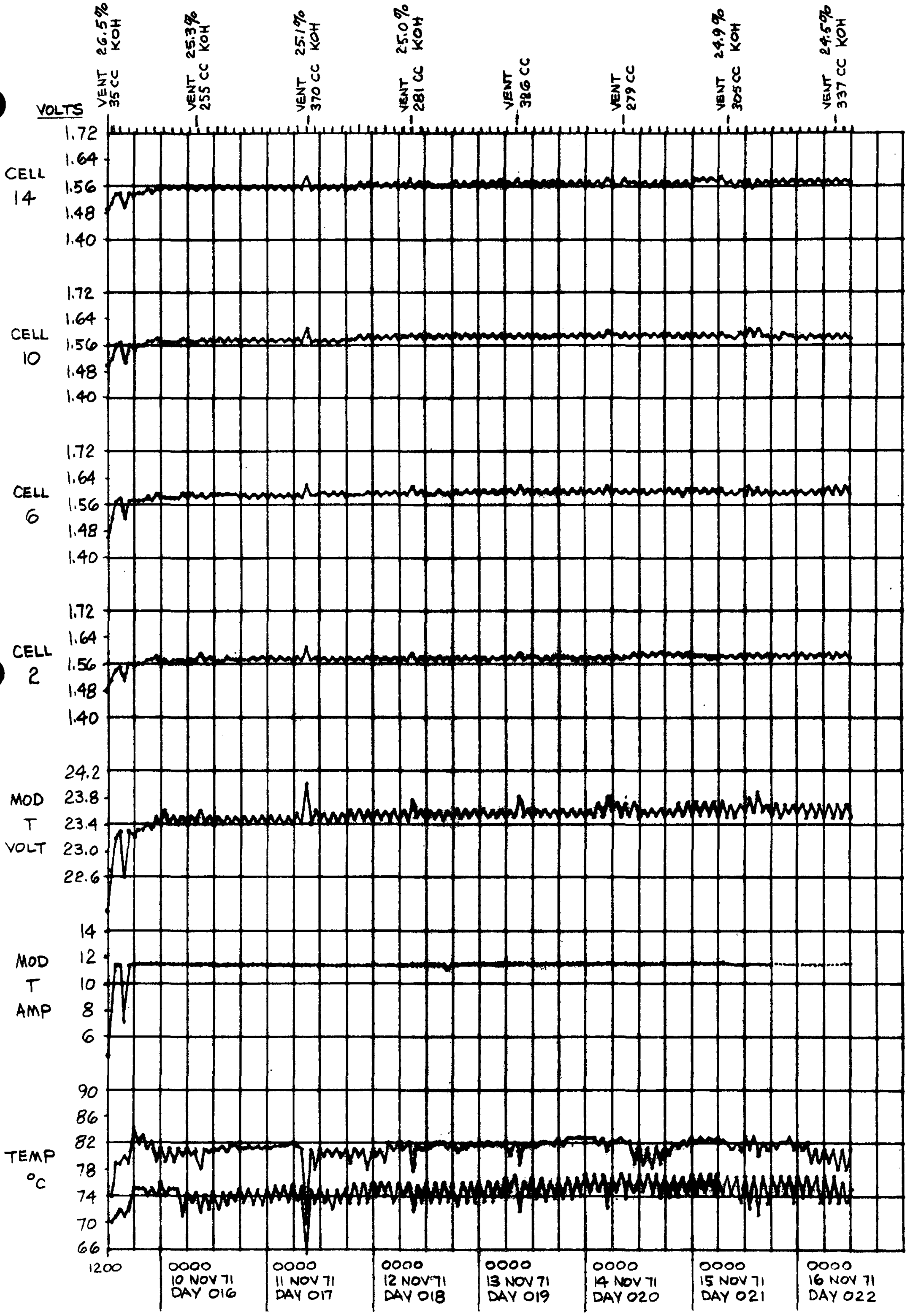


FIGURE 5-60 PERFORMANCE HISTORY (POSITION 2- MODULE 2)

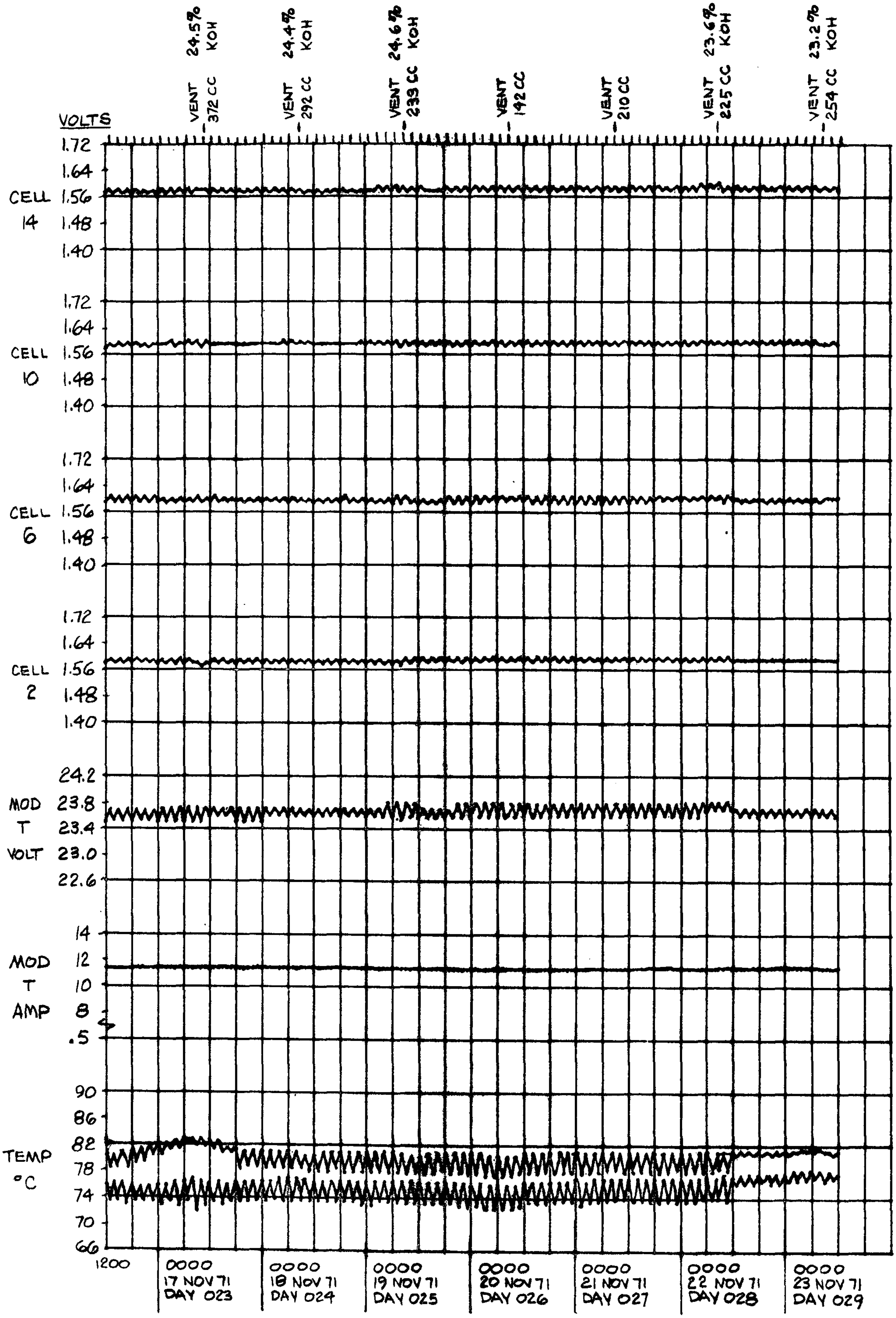
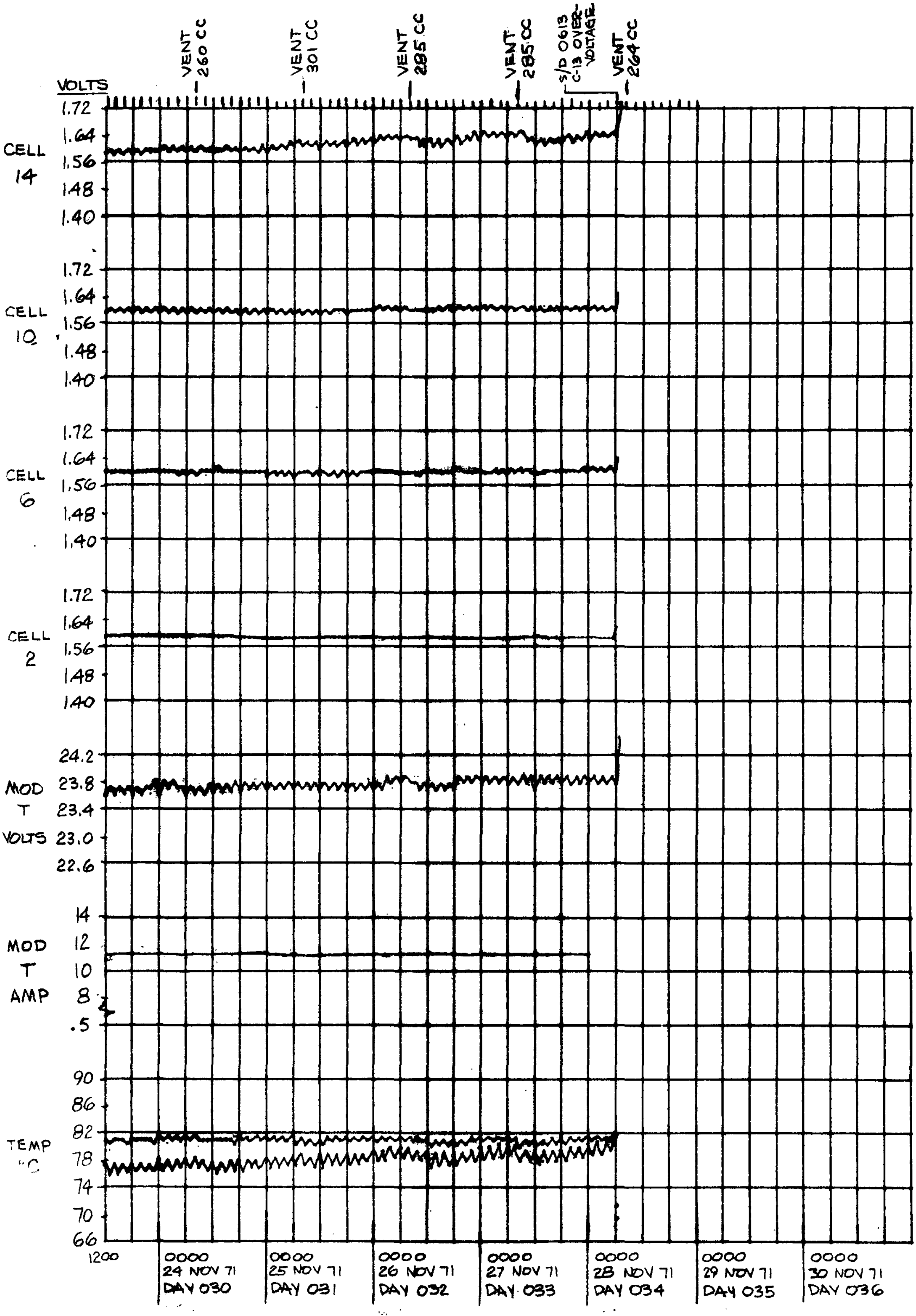


FIGURE 5-61 PERFORMANCE HISTORY (POSITION 2- MODULE 2)



module. The module was reassembled, pressure checked, cross-leak checked, and flushed in preparation for reuse. The module was restarted at 1150 on 16 December and operated at 11.3 amperes until 0730 19 December at which time the operator reduced the current to 4.5 amperes. Inspection of the data printout revealed that the module was over voltage in cell 9 at 0601 that morning. The computer tried to shut the module off but the module electronics never received the signal. The module was left in that condition until the total system was shutdown due to out of tolerance pressure conditions at 2046 on 19 December. Figures 5-62 and 5-63 show the overall performance of the module and the details of the out-of-tolerance condition. Damage to the module was not apparent. After removal from the system all cavities were drained and the samples analyzed. The results are as follows:

H_2O Cavity	118 cc's	24.1% KOH concentration
H_2 Cavity	42 cc's	24.3% KOH concentration
O_2 Cavity	32 cc's	23.6% KOH concentration

It should be pointed out that this was the last module removed from the system after shutdown and therefore had the longest time (19 hrs) to equalize cavity concentrations.

Inspection of the module did not indicate any problems, thus the module was flushed and restarted in the system at 0906 on 23 December. A short term system shutdown occurred at 1646 due to the differential pressure switch being improperly set. The system was restarted at 1750 and this module operated until 0417 on 27 December. Shutdown occurred due to overvoltage in cell 9. Figure 5-64 shows the performance of the module during this time period. The module was pulled from the system and all cavities drained and the samples analyzed. The results of the sample, collection and analysis and flushing of each cavity is as follows:

FIGURE 5-62 PERFORMANCE HISTORY (POSITION 2-MODULE 2)

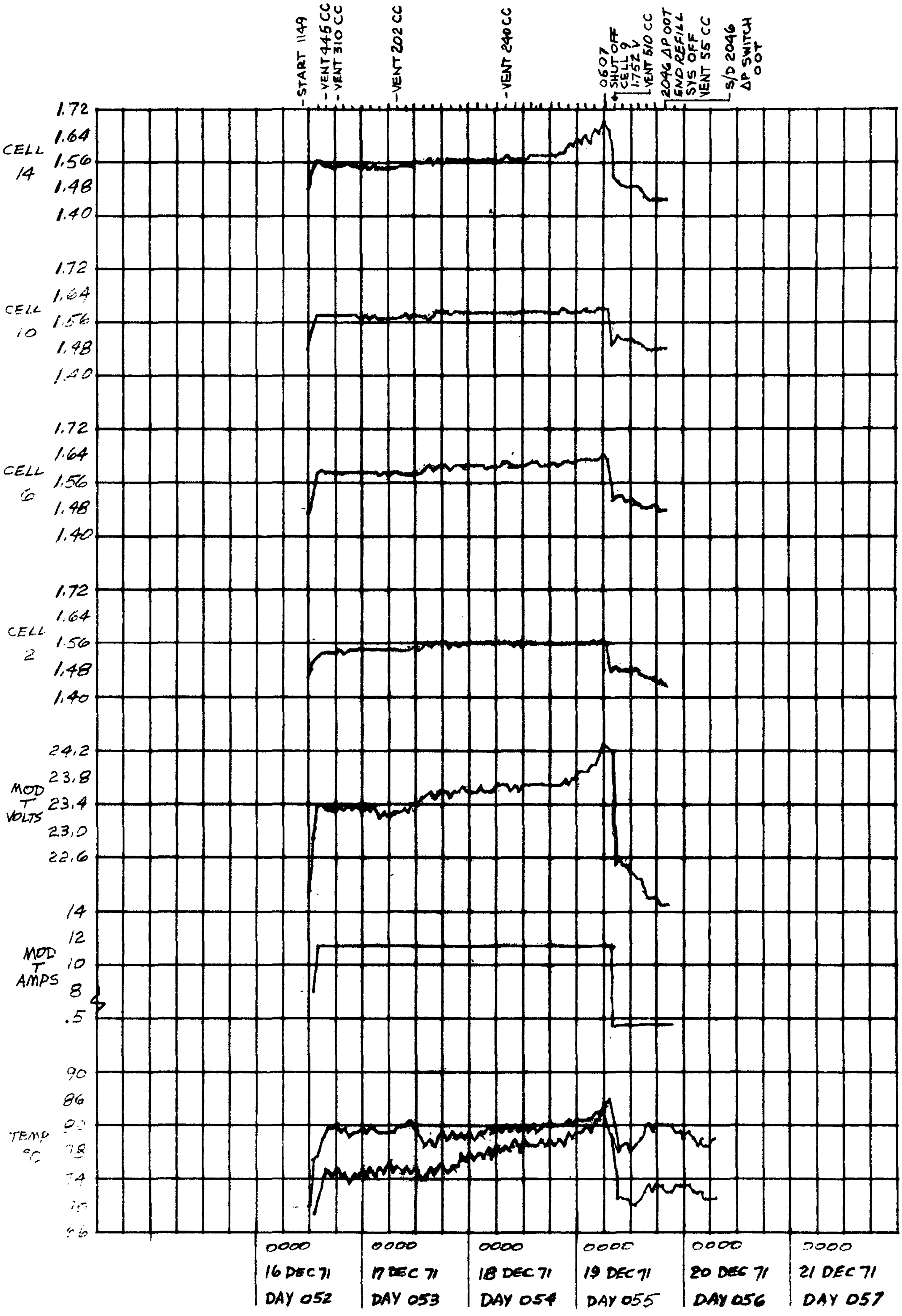
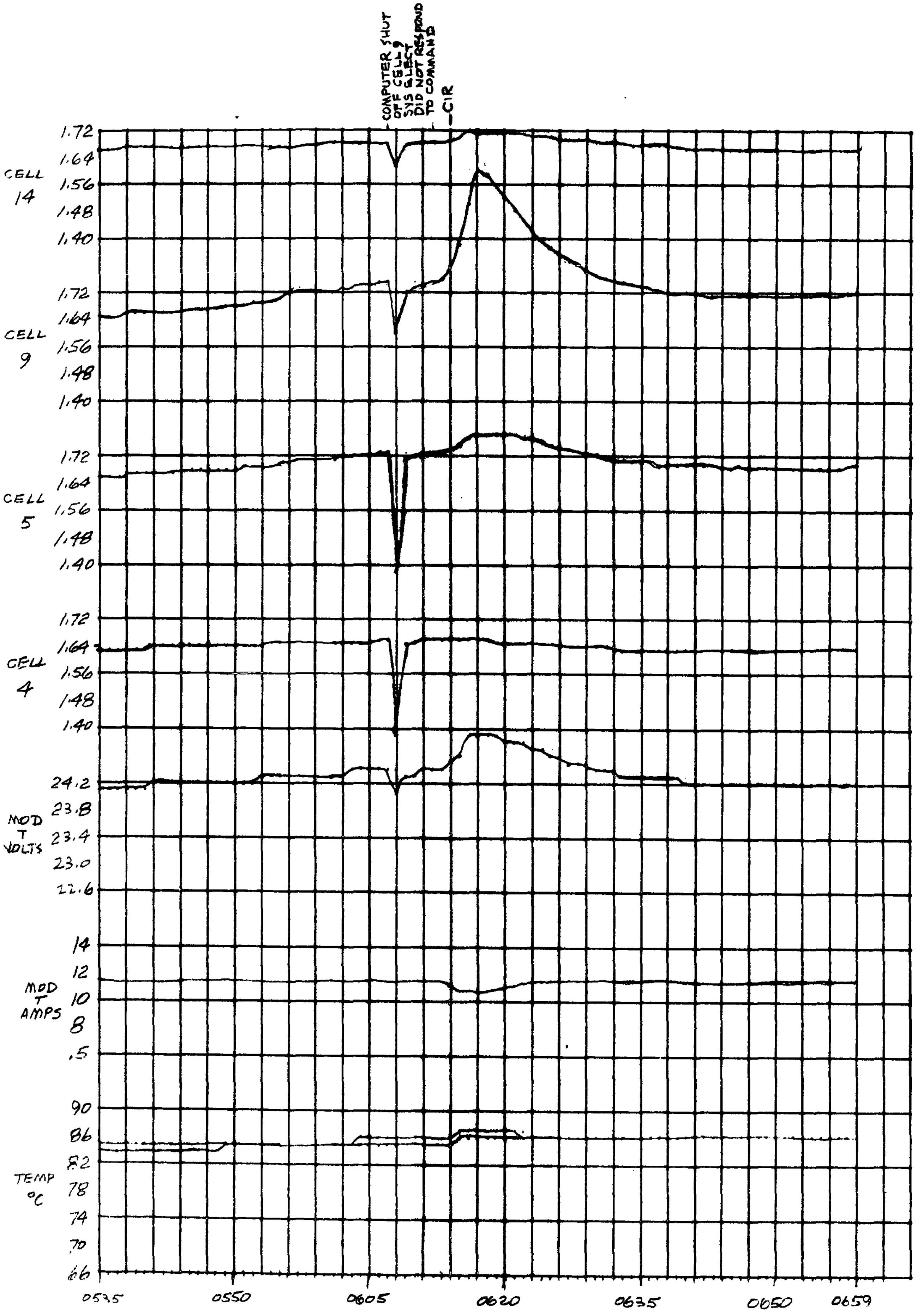
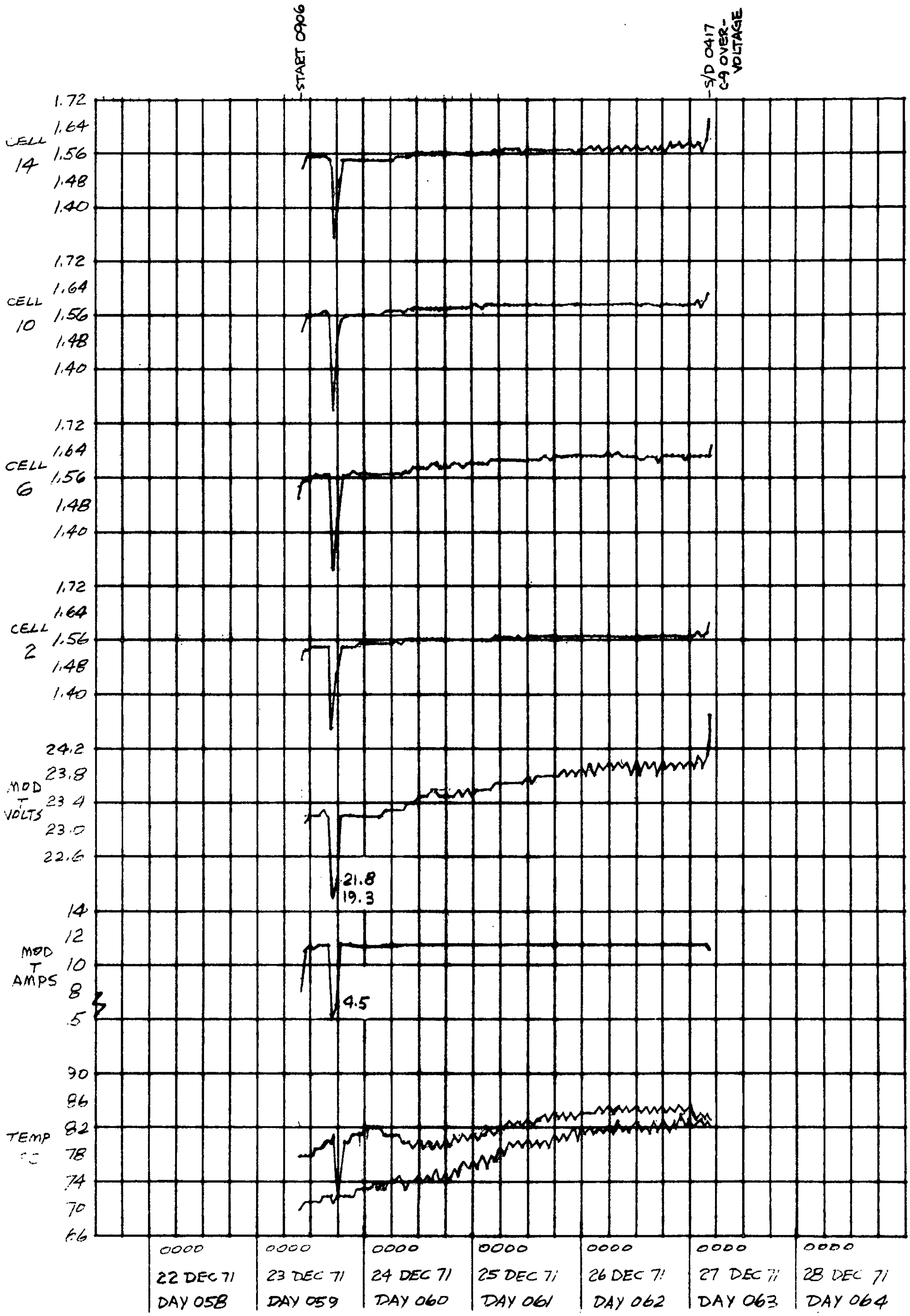


FIGURE 5-63 PERFORMANCE HISTORY (POSITION 2-MODULE 2)



19 DEC 71 DAY 055

FIGURE 5-64 PERFORMANCE HISTORY (POSITION 2 - MODULE 2)

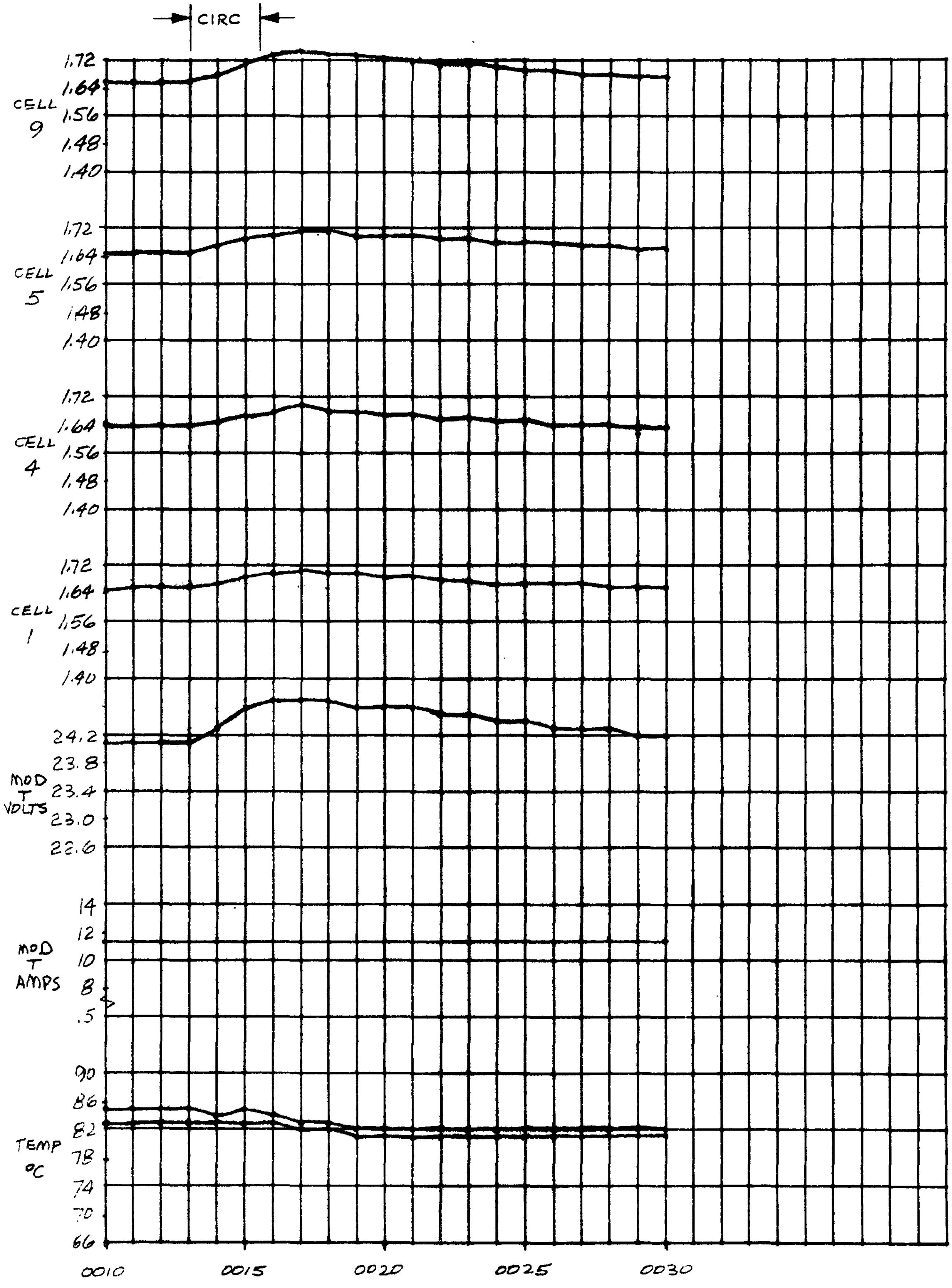


Cavity	Liquid Sample Quantity	Concentration	Flush Cart Concentration Initial	Flush Cart Concentration Final
H_2O	107 cc's	31.2%	30.4%	30.3%
H_2	9 cc's	28.7%	30.2%	30.4%
O_2	Zero	--	29.9%	30.2%

This module had been subjected to two circulations and 4 hours of sitting after shutdown and prior to sample collection. Flushing of the individual cavities of the module did not occur until 7 days after shutdown. Therefore, the most meaningful information can be obtained from the samples rather than from the flush cart data. The samples indicate no flooding of the oxygen cavity and a high concentration of electrolyte in the water cavity. The implication is that KOH was collecting in the water matrix and not being washed out by the normal circulation or by back diffusion. High KOH concentration in the water matrix requires a volumetric change in the liquid in the electrolyte matrix to obtain an adequate vapor pressure differential for water vapor transfer. The volumetric change may have been too great thus creating high resistance and high cell voltages. Figures 5-65 through 5-67 show the change in cell voltage for the four worst performing cells in the module for the two periods of electrolyte circulation prior to shutdown and the circulation period causing shutdown. In each of the two circulations preceding shutdown the module and cell values returned almost to normal within 20 minutes following the circulation. In each early case cell 9 rose very close to the shutdown level, in the final case the level was exceeded. This indicates that the KOH buildup in the module occurred over a long period of time rather than just prior to shutdown.

The module was restarted at 1200 on 11 January and operated until 1627 on 13 January when it was shutdown manually. At that time it was the only module operating and appeared that it would not continue operating all night. Module voltage was 23.7 at only 8 amperes current. Cells 1, 4, 6 and 9 were all at 1.6 volts or over. The module was removed from the

FIGURE 5-65 CIRCULATION EFFECTS (POSITION 2 - MODULE 2)



27 DEC 71 DAY 063

FIGURE 5-66 CIRCULATION EFFECTS (POSITION 2-MODULE 2)

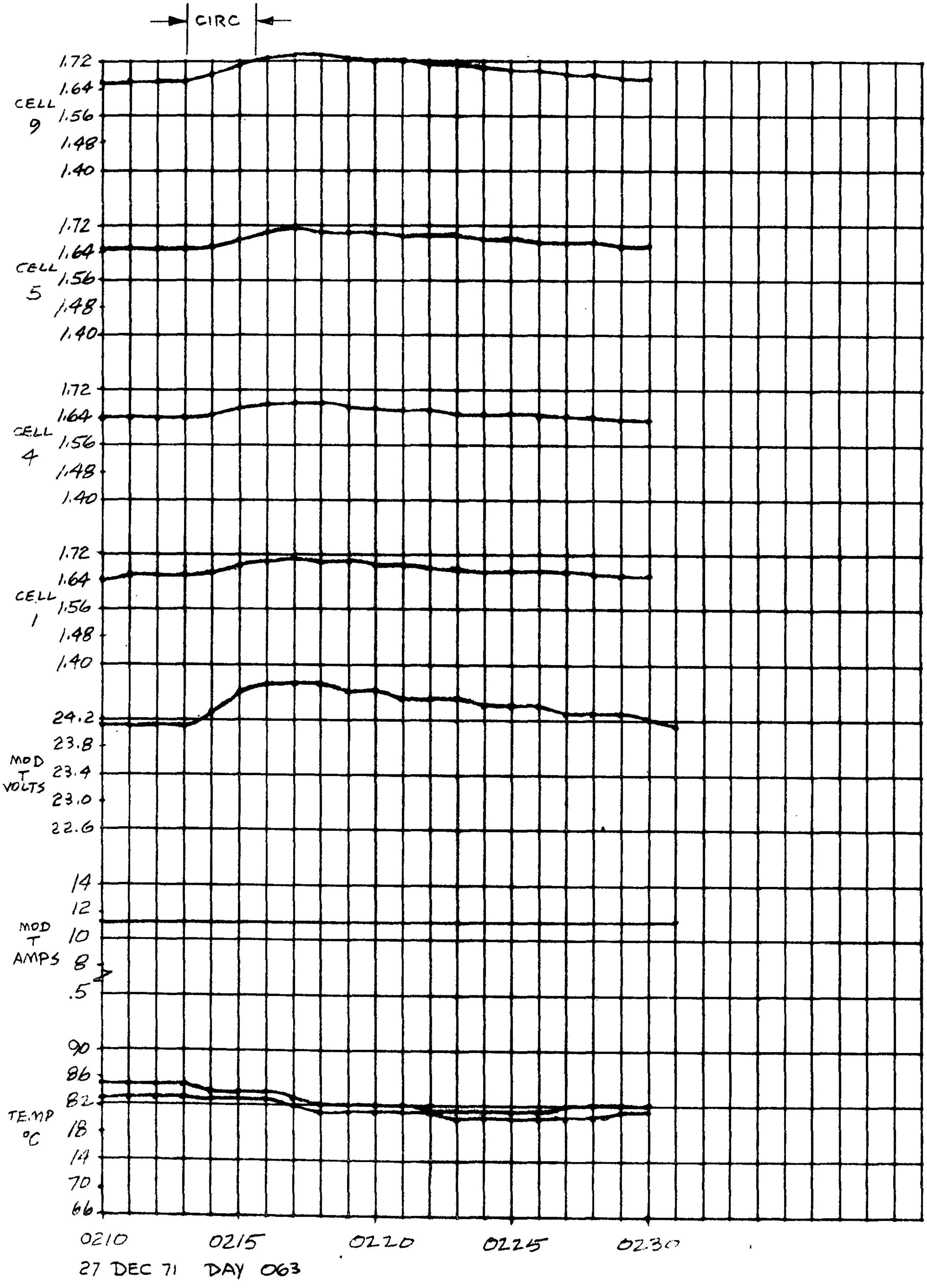
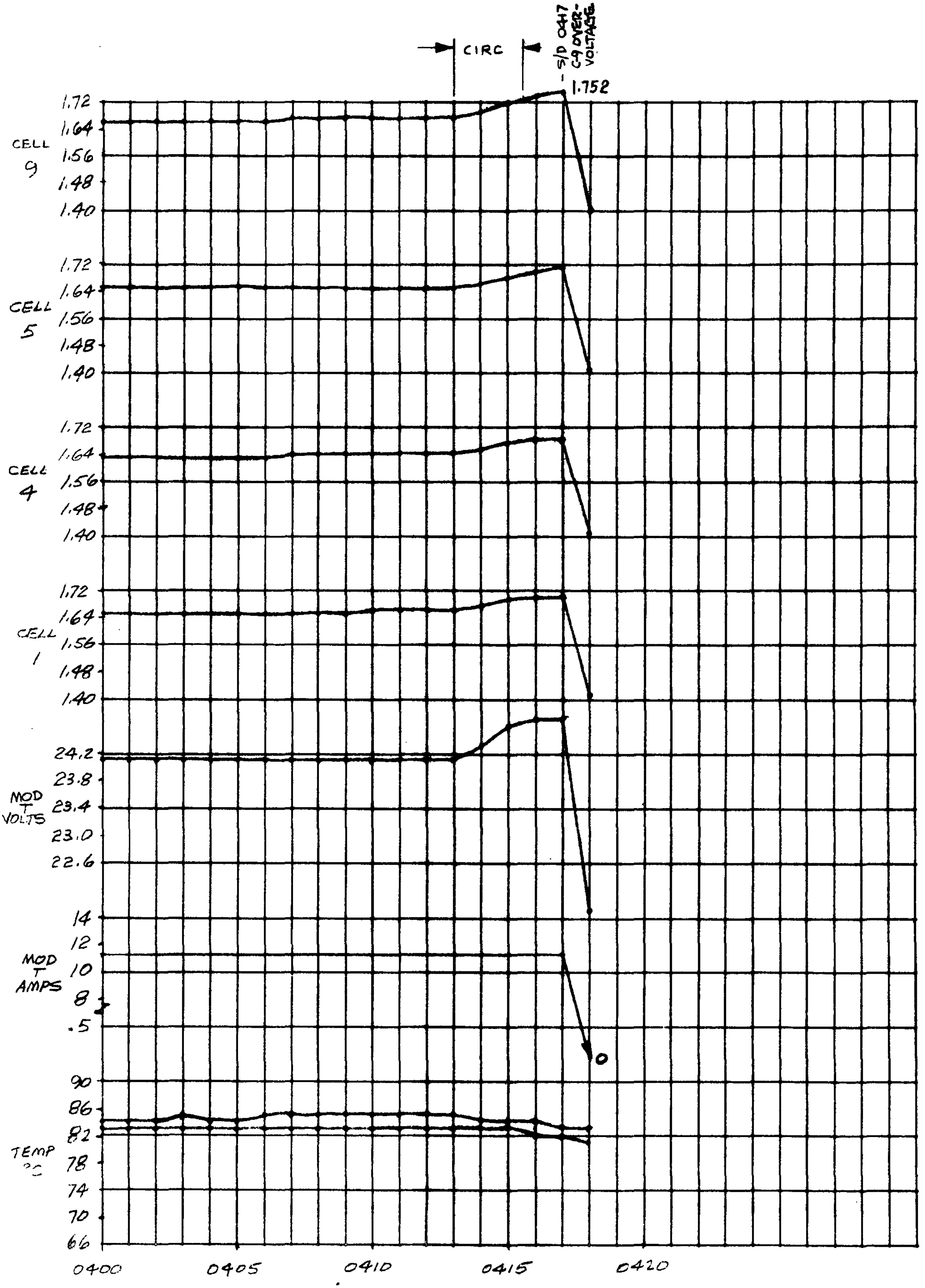


FIGURE 5-67 CIRCULATION EFFECTS (POSITION 2 - MODULE 2)



27 DEC 71 DAY 063

system, flushed, inspected and prepared for reuse. Flush cart concentration changed from 33.5% KOH to 34.0% KOH with all cavities of module 2 on overnight. The module appeared in good condition. See Figure 5-68 for performance data.

The module was restarted at 1345 on 14 January and operated until 2217 on 16 January when it was shutdown automatically due to overvoltage in cell 9 (see Figure 5-68). The module was removed from the system on 17 January. All cavities were drained and the samples analyzed. The results are as follows:

H_2O cavity	126 cc liquid	30.5% KOH
H_2 cavity	21 cc liquid	32.7% KOH
O_2 cavity	zero liquid	- - - - -

The loop concentration was 25.0% KOH at this time. Each cavity of the module was flushed separately. The results are as follows:

Cavity	Flush Cart Concentration Initial	Flush Cart Concentration Final
H_2O	30.40%	30.75%
H_2	30.75%	30.90%
O_2	30.90%	31.0%

The module was inspected, cross leak checked and external leak checked. No anomalies were encountered and hence the module was considered ready for reuse.

The module was restarted at 0949 on 20 January and operated until 1429 on 22 January (See figure 5-69). Shutdown was due to loss of 115 volt AC power supply which shutdown the signal conditioning console and as a result the computer shut down the total system. Performance for these two days

FIGURE 5-68 PERFORMANCE HISTORY (POSITION 2- MODULE 2)

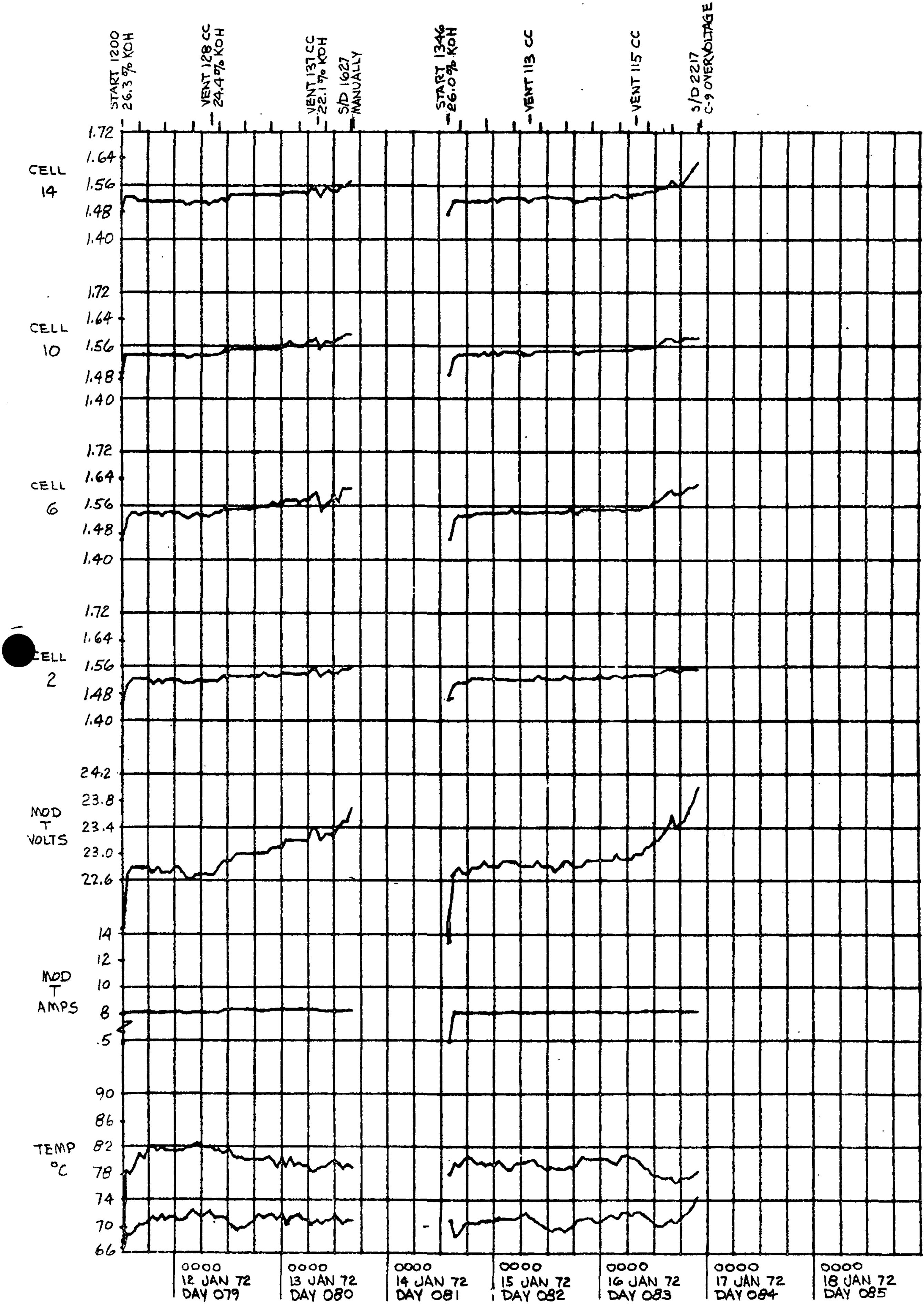
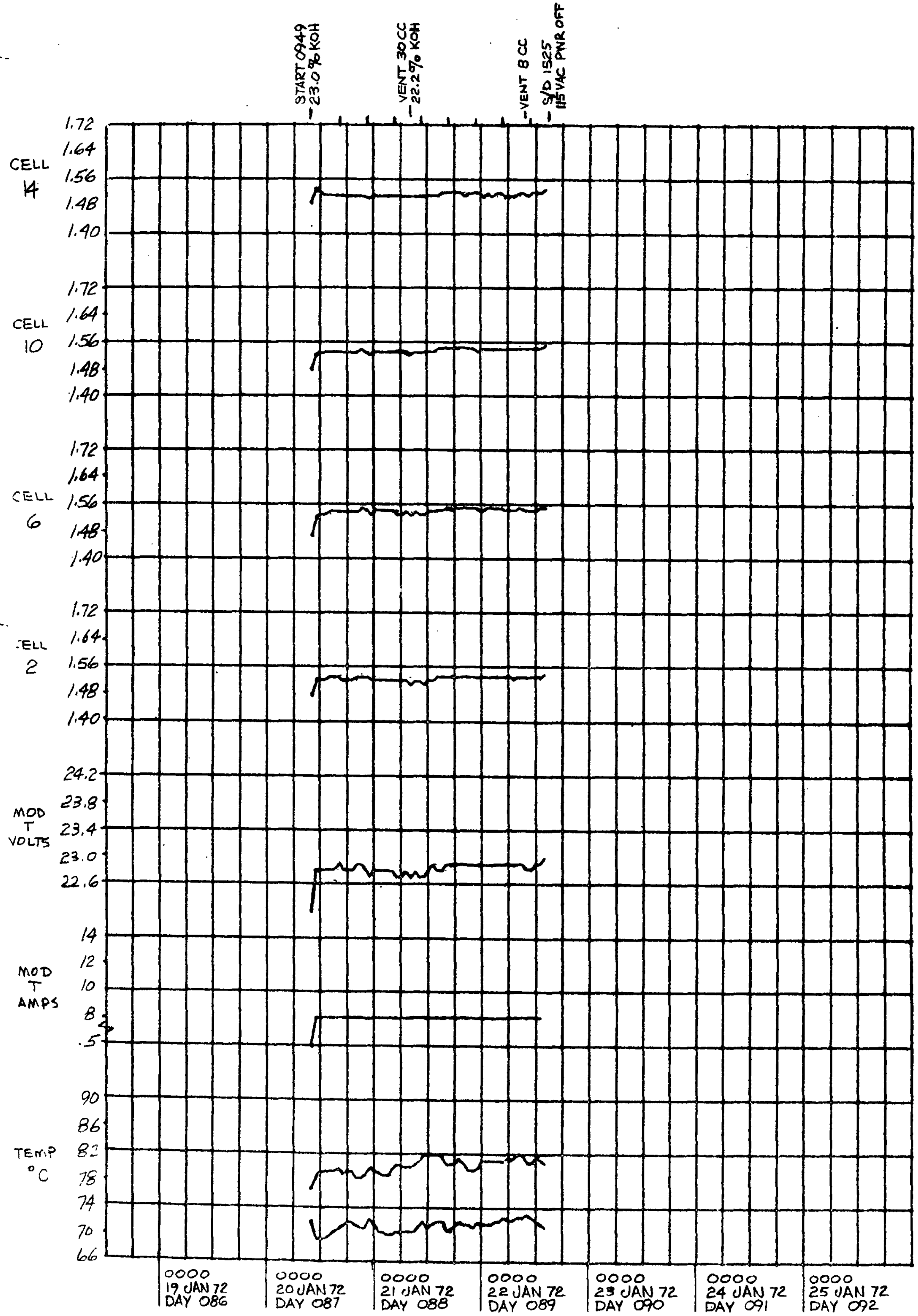


FIGURE 5-69 PERFORMANCE HISTORY (POSITION 2 - MODULE 2)



was very stable. Circulation was 10 minutes every 6 hours and initial system concentration was 23.0% KOH. Matrix concentration was retained at 30.0 to 30.5% KOH. on 24 January the modules was removed from the system and all cavities drained and the samples analyzed. The results are as follows:

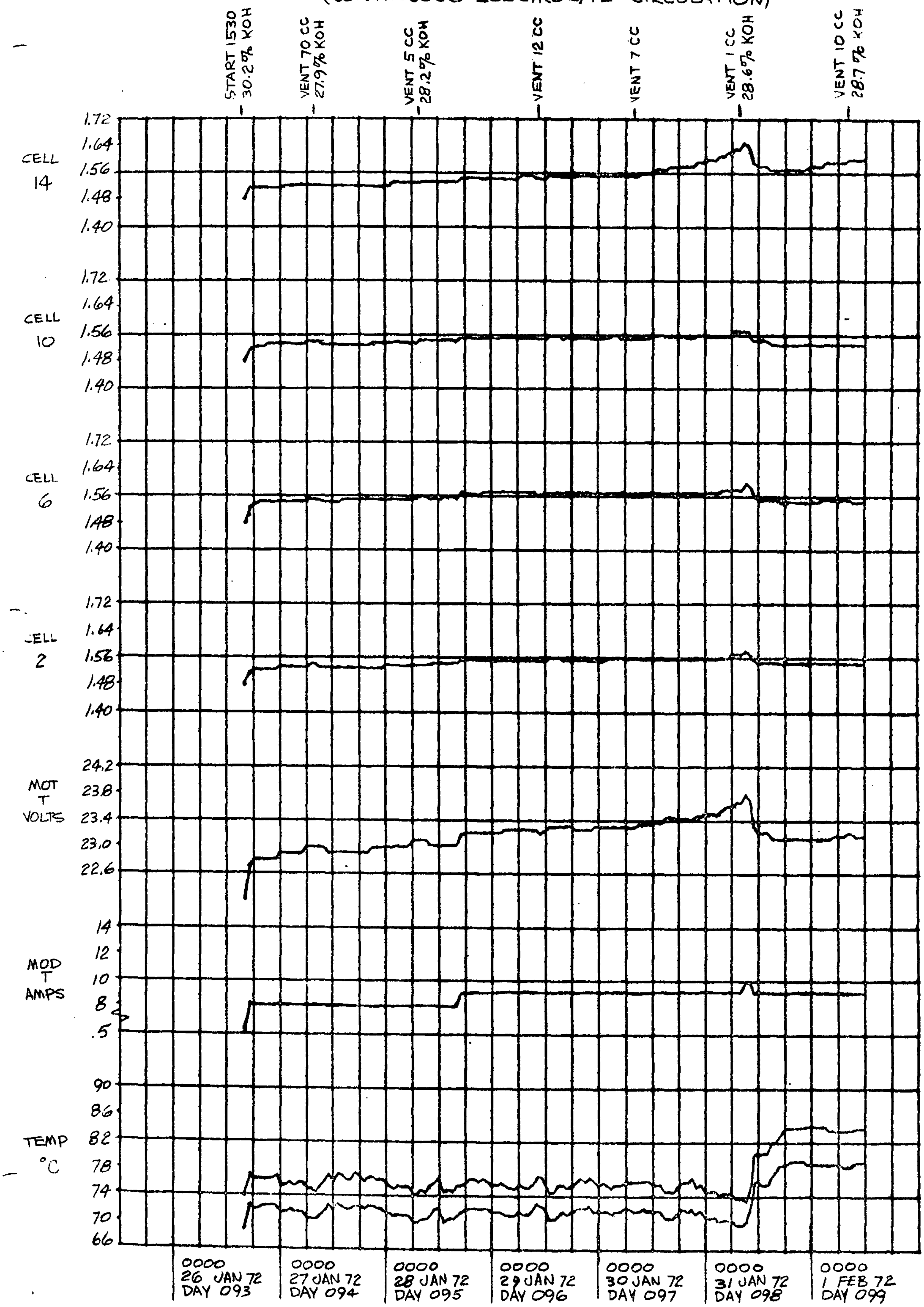
H_2O Cavity	135 cc liquid	26.7% KOH
H_2 Cavity	4 cc liquid	30.0% KOH
O_2 Cavity	4 cc liquid	30.0% KOH

The system electrolyte concentration 42 hours after shutdown was 20.6% KOH. After flushing all cavities of the module for 3 1/2 hours the flush cart concentration changed from 32.0% KOH to 30.7% KOH. The module was inspected and checked and was found in good condition and ready for reuse after proper concentration adjustment.

The module was restarted at 1530 on 26 January with continuous electrolyte circulation and all parts of the module and system at 30.2% KOH. Module voltage showed a gradual increase until 31 January when it was decided that system and module temperatures were too low. Temperatures were increased from an average of 344°K (160°F) to 353°K (176°F). This brought the module voltage down and showed more stable performance. The module was still operating at 9 amperes at the end of this time. Figure 5-70 shows the specific performance of this module during this period.

The module continued operating until 2253 on 5 February. The cause of shutdown was an overtemperature condition in TC1. The overtemperature condition was caused by the circulating pump failure as explained earlier. During the operating period the module current reached a maximum of 10 amperes. It remained at this level for approximately 36 hours. Thereafter the current was reduced at 1/2 ampere

FIGURE 5-70 PERFORMANCE HISTORY (POSITION 2- MODULE 2)
(CONTINUOUS ELECTROLYTE CIRCULATION)



increments every 24 hours to reduce the rate of increase of cell and module voltages. After the failure the module was removed from the system and all cavities drained. Figure 5-71 shows the performance of the module during the period. The H_2 cavity had 34 cc. The O_2 cavity was dry of liquid and the H_2O cavity was full of liquid (approximately 155 cc's). The module was inspected carefully and approximately two cc's of KOH were removed from the exterior of the module at the lower heater tabs of cells 4 through 7. Small quantities of KOH were also found between cells 2 and 3 (at electrode area) and also on cells 3 and 4. Cells 2 and 3 had additional KOH at the top of the module near the electrodes. Cells 6 and 7 also had KOH at this location. The module was placed on the flush cart and caused the flush cart concentration to rise from 29.9 to 30.2% KOH within 1 hour of flushing. An additional 16 hours of flushing did not change the concentration in the flush cart. Analysis of the total KOH collected from both module 2 and 3 showed the quantity to be 4.4 grams. About half came from each module. No other corrections or changes were made to the module.

On 9 February at 1218 the module was restarted and ran until manually shutdown at 1313 on 16 February. The manual shutdown was selected because the cell voltage in cell 14 was high and modifications to the plumbing were ready to be made. Figures 5-72 and 5-73 show the performance of the module during this period. The varying temperature in the module on test days 108 through 110 was caused by opening and closing the large bay doors on the laboratory building. This caused a large air flow across the test systems. A 2.13 m (7 foot) high wall was built to block this adverse air flow and temperatures showed less cyclic variations. Inspection of the module after removal showed some KOH on the lower heater tab at cell 6. A very small amount of KOH on the module bottom between cells 1 and 2, cells 2 and 3, cells 3 and 4, cells 12 and 13, and cells 14 and 15. A small leak was evident on the water inlet fitting. A large deposit of KOH existed on the electrode at cell 2 and 3 (bottom). This deposit has caused partial splitting of electrode screen solder joint. A moderate amount of KOH was

FIGURE 5-71 PERFORMANCE HISTORY (POSITION 2 - MODULE 2)

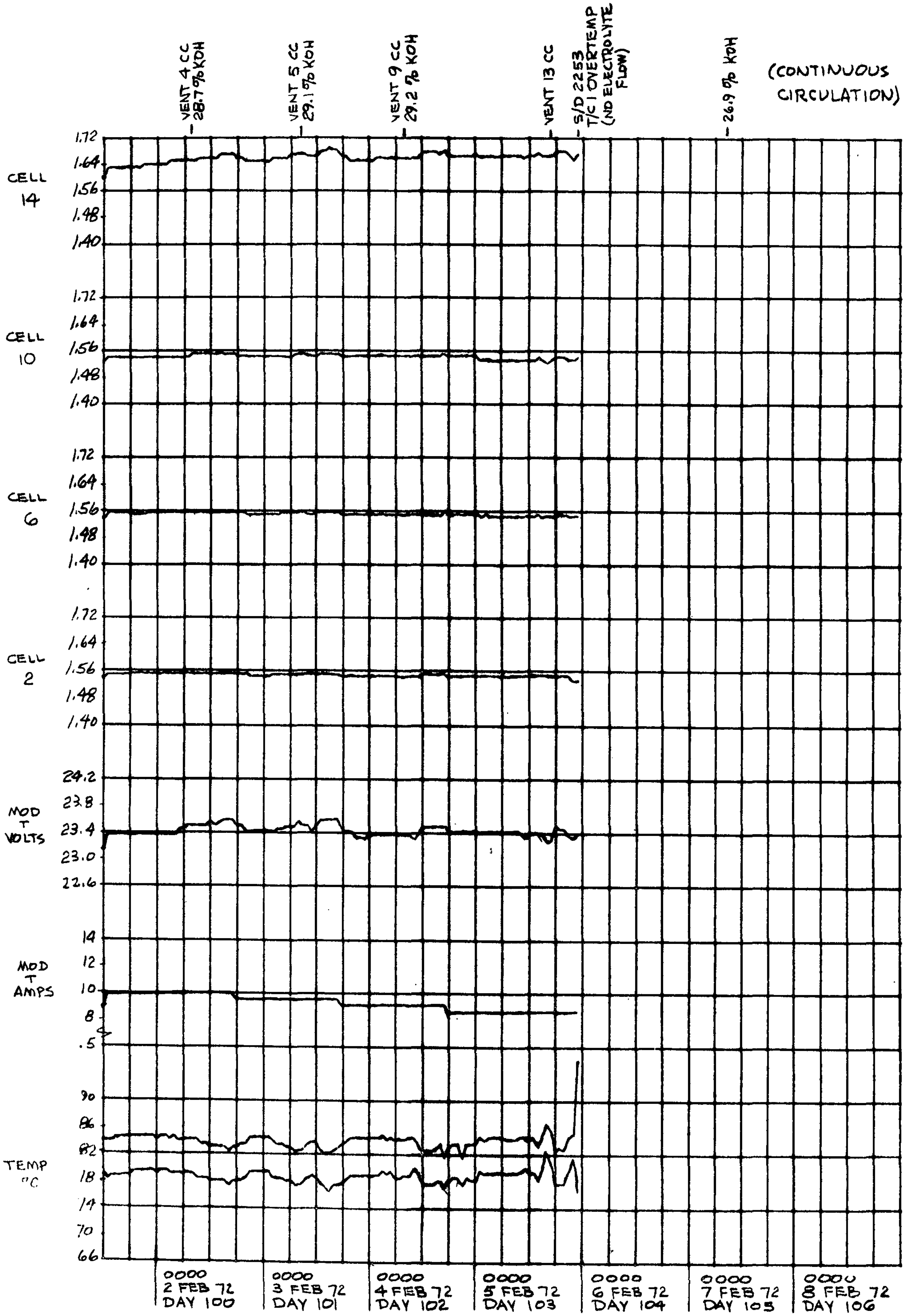


FIGURE 5-72 PERFORMANCE HISTORY (POSITION 2 - MODULE 2)

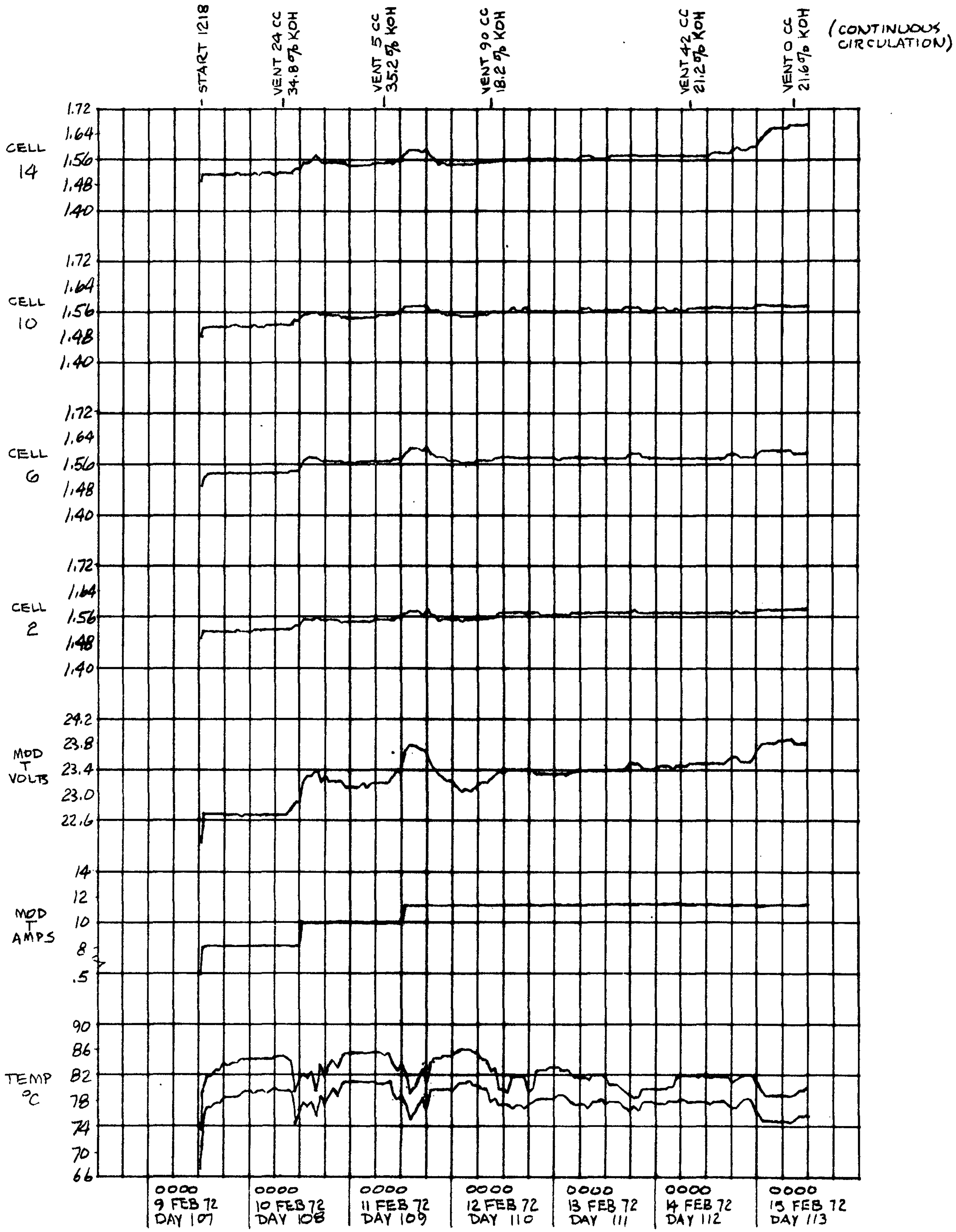
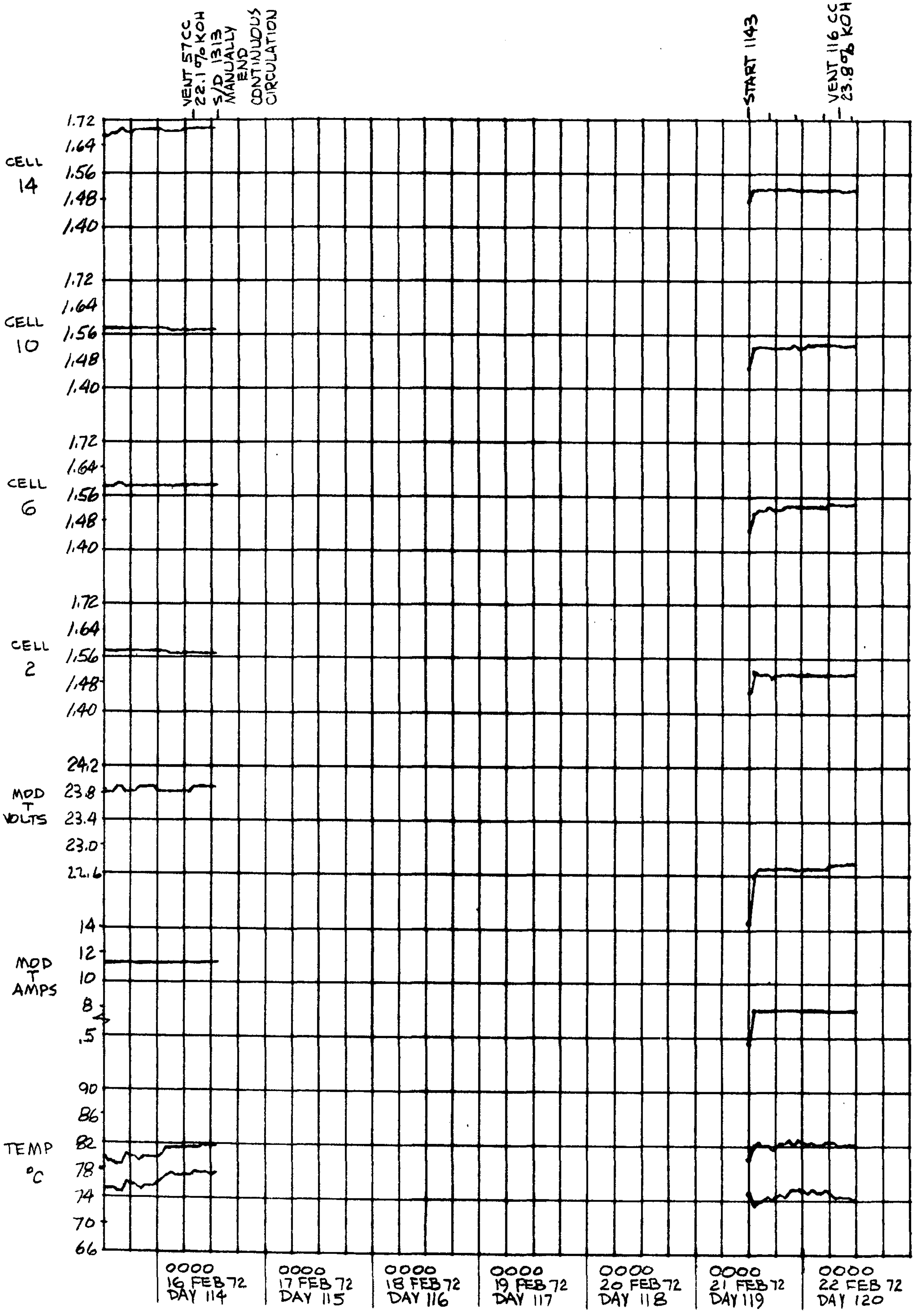


FIGURE 5-73 PERFORMANCE HISTORY (POSITION 2- MODULE 2)



found at the cell 6 and 7 interface at the upper end of the electrode. Generally speaking the module looked good. The module was considered in good enough condition not to require disassembly. It was cleaned up and placed on the flush cart. After 70 minutes on the flush cart the concentration had changed from 29.3% to 28.9% KOH. All heater resistances were checked on the module and were found to vary between 145 ohms and 340 ohms. The majority were about 150 ohms. All soldered joints were checked and a few were resoldered where it was deemed necessary. The module was then flushed with 30.2% KOH.

At 1143 on 21 February, the module was restarted. It continued to operate until 0158 on 26 February when it was shutdown by the computer for an overvoltage condition in cell 1. Cell 13 showed very unusual behavior on 24 and 25 February. The performance is shown on Figure 5-74. The first manual circulation to add KOH to the loop on 24 February seemed to cause cell 13 to rise rapidly. The cell stayed at a high level until 1015 on 25 Feburary. From that point on each circulation seemed to cause an improvement in the performance of the cell. The second addition of KOH on 25 February caused a significant recovery of cell 13. It appears that the cell was starved for KOH. Cell 1 on the other hand, showed a degradation in performance each time KOH was added and a circulation took place; possibly implying an excess of KOH in the cell. Figure 5-75 shows the profile of cell voltages within the module 2 hours before and after each addition of KOH. Also shown are the cell voltages 2 hours before shutdown. This module developed a rather significant leak during this period of operation. The addition of KOH to the loop was to makeup that KOH lost through the leak.

The module was removed from the system on 26 February approximately 7 hours after shutdown. All cavities were drained. The results are as follows:

H_2O cavity	57 cc	32.2% KOH
H_2 cavity	20 cc	34.0% KOH
O_2 cavity	1.5 cc	30.6% KOH

FIGURE 5-74 PERFORMANCE HISTORY (POSITION 2- MODULE 2)

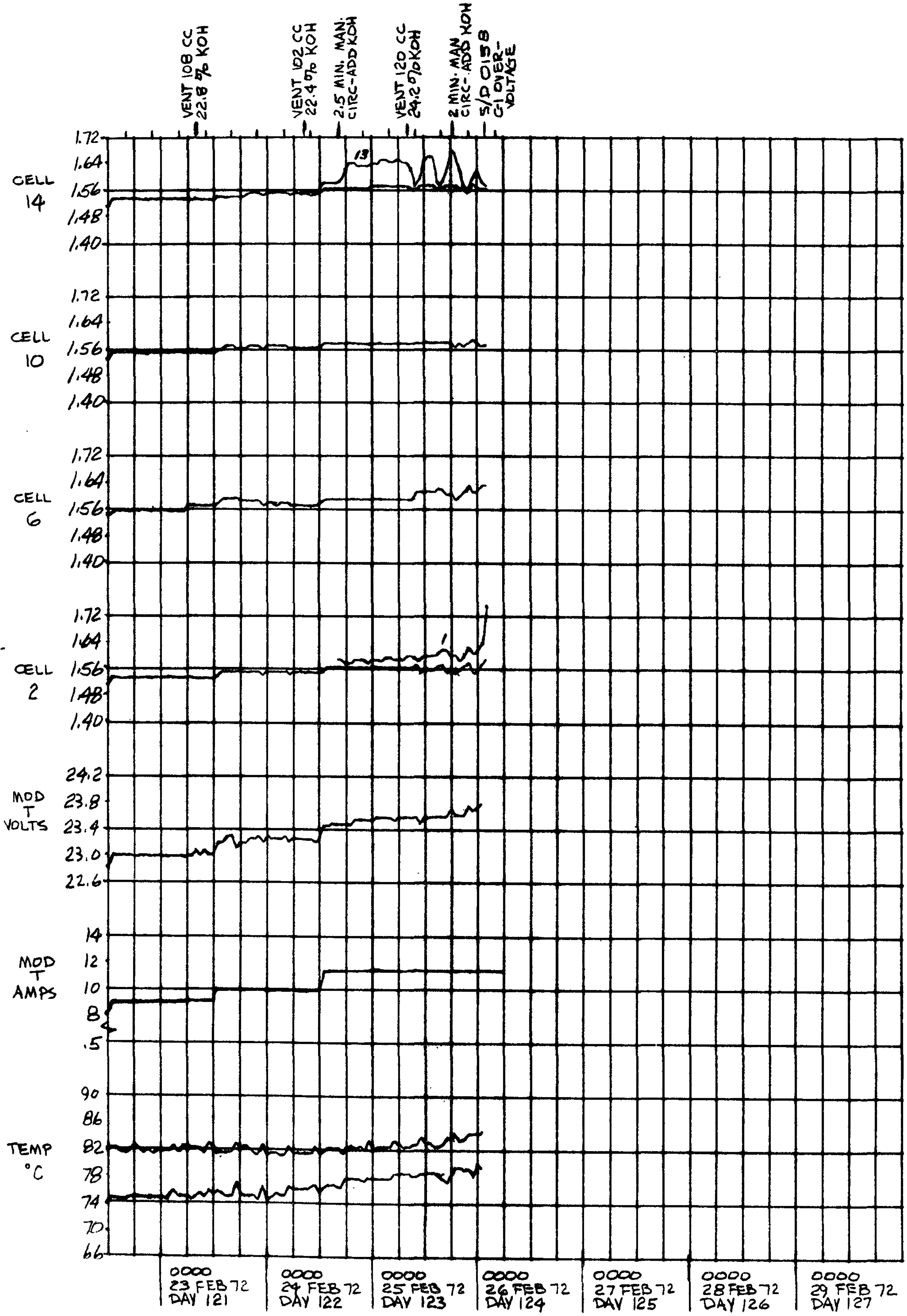
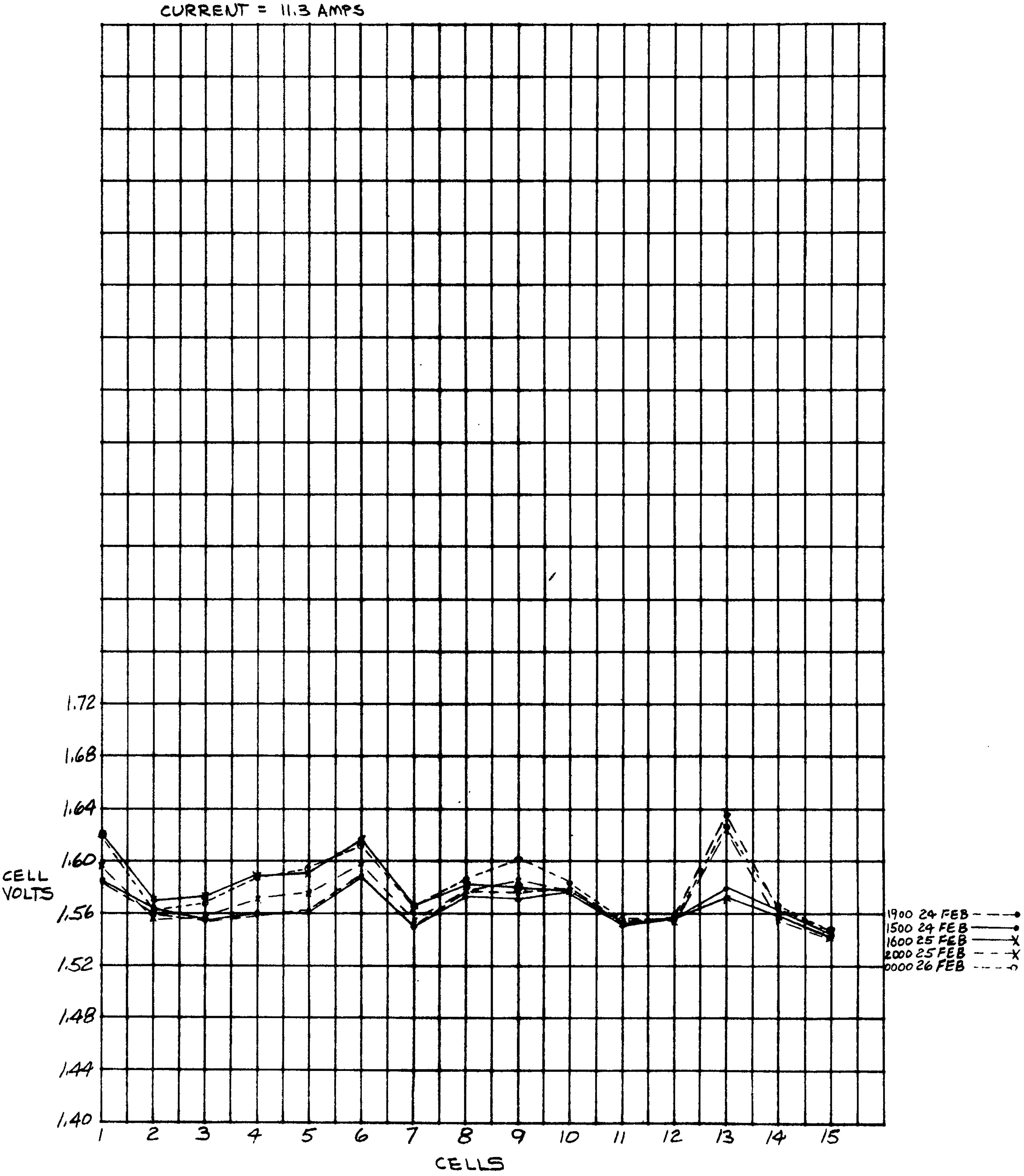


FIGURE 5-75 MODULE VOLTAGE PROFILE (POSITION 2- MODULE e)

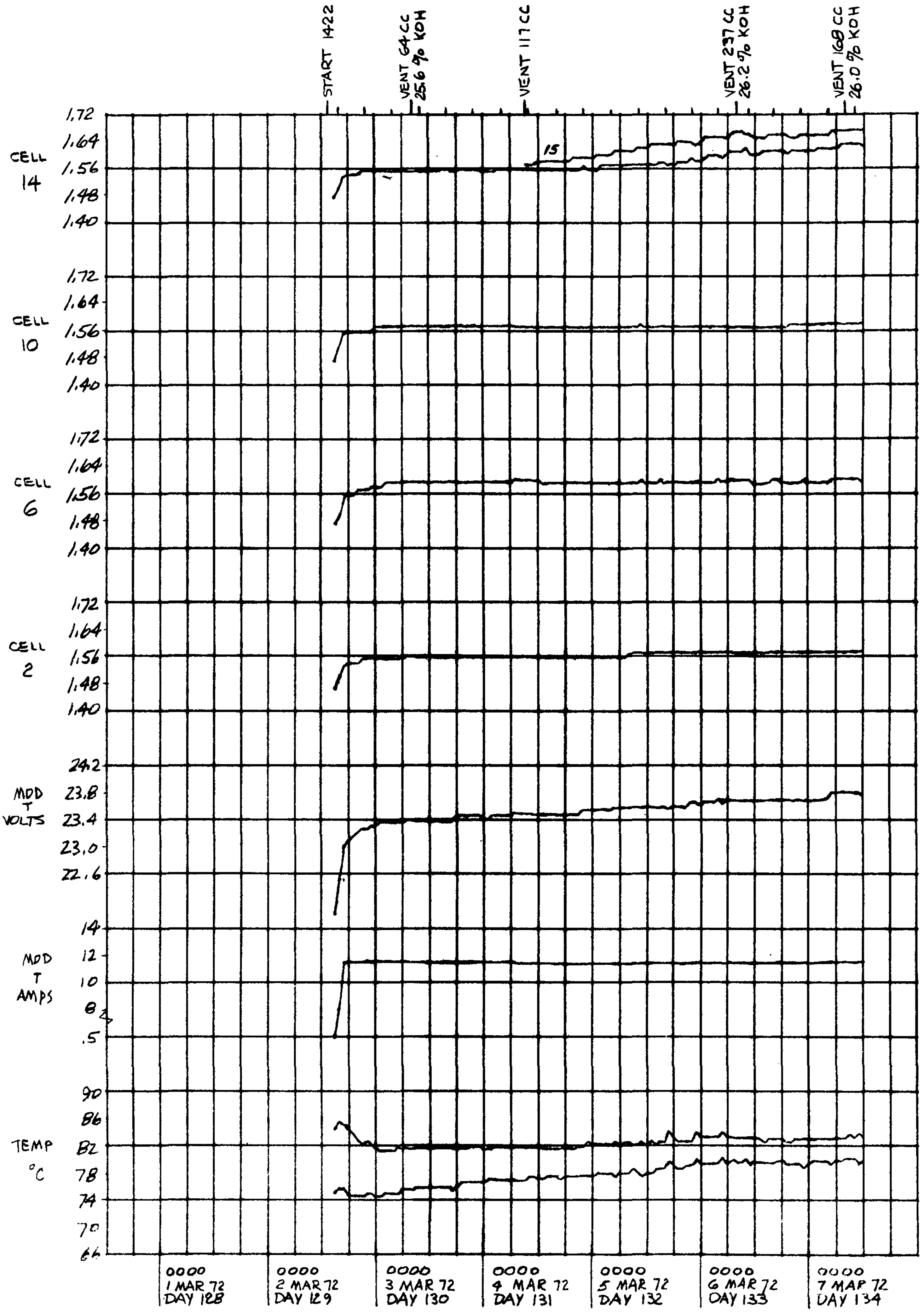


Inspection of the module showed KOH accumulations on front endplate and evidence of leakage on H_2O inlet Swagelok tube. A slight KOH accumulation was found at cell 6 lower heater tab. Approximately 2 cc's of KOH had accumulated at cells 1, 2 and 3 electrode screens. Slight quantities of KOH deposits were found on cells 1 through 7 below electrode screens on the side of the module. It is believed that this KOH was carried up from the bottom of the thermal box by capillary action. It is estimated that approximately 115 grams of KOH were lost from the leak in the module during the 4 1/2 days of operation.

The module was disassembled and each cell inspected carefully. A crack was found in cell 1 H_2O cavity to the exterior of the cell between cell 1 and the front spacer plate. This crack was at a point in the cell directly under the edge of a 0.025 cm (0.010 inch) shim which was located on the H_2O cavity side of the cell. The crack allowed KOH to contact the cell 1 heater. Evidence of heat and two burned spots were found in the plastic at the intersection of the crack with the heater wire. Evidence was also found that the KOH leaking from cell 1 had come in contact with some of the cell screens, causing a parallel conduction path around the electrode matrix. Studs which passed through the electrodes were also badly eroded. The studs were replaced with spares.

The repairs to this module were completed and the module was started at 1422 on 2 March. It operated until 1017 on 8 March. Performance is shown on Figure 5-76. Cause of shutdown was an out-of-tolerance condition in cell 14. Review of the printout data showed cell 15 was also at an out-of-tolerance level. Shutdown was manual because the shutdown signal from the interface unit never reached the module. The problem was traced to a malfunction in electronic flip-flop logic element. The chip was replaced and shutdown signals checked out. The proper response was recorded by the system.

FIGURE 5-76 PERFORMANCE HISTORY (POSITION 2-MODULE 2)



After the shutdown the module was inspected and found to be in good condition. The plumbing on the module was modified to allow feed water to enter the top of the module instead of the bottom. The module was restarted at 1601 on 8 March and operated until automatically shutdown at 1017 on 16 March due to overvoltage in cell 15. The module was removed and inspected. The inspection revealed small quanities of KOH at a number of locations. All the quantities were very small. Cells 6 and 1 instrumentation leads were loose or not connected. The module was suspected of having internal leaks and stray electrolysis and was therefore disassembled. All the cavities were drained within 25 minutes of shutdown. The H_2O cavity contained 133 cc of liquid at a concentration of 25.9% KOH. This is slightly higher than the loop concentration which was 25.2% KOH. It appeared that some KOH concentrating had occurred in the water matrices. The O_2 and H_2 cavities had less than 0.5 cc of liquid which was insufficient for concentration analysis. The performance of the module during the period is shown on Figures 5-77 and 5-78. The data indicates higher than usual module and cell voltages and cyclic variations that correlate directly with the module circulations. Cell and module voltages dropped right after a circulation, presumably because trapped gas has been removed and there was less restriction to feed water entering the module.

Cell 13 was replaced in the module due to apparent contact between electrolyte and cell heater wire. The module was reassembled and restarted with bottom water feed at 1437 on 22 March. Operation at this time was with only 14 cells as cell 15 was to be used as a liquid bypass line. The module operated until 1017 on 27 March when cell 14 went out of tolerance. Module performance is shown on Figure 5-79. Using cell 15 as a bypass did not seem to work as cell 14 went out of tolerance in less time than expected. The module was found to be in good condition and was therefore not removed from the system but allowed to equalize until 0806 on 28 March at which time it was restarted. It continued to operate until 1017 on 1 April.

FIGURE 5-77 PERFORMANCE HISTORY (POSITION 2 - MODULE 2)

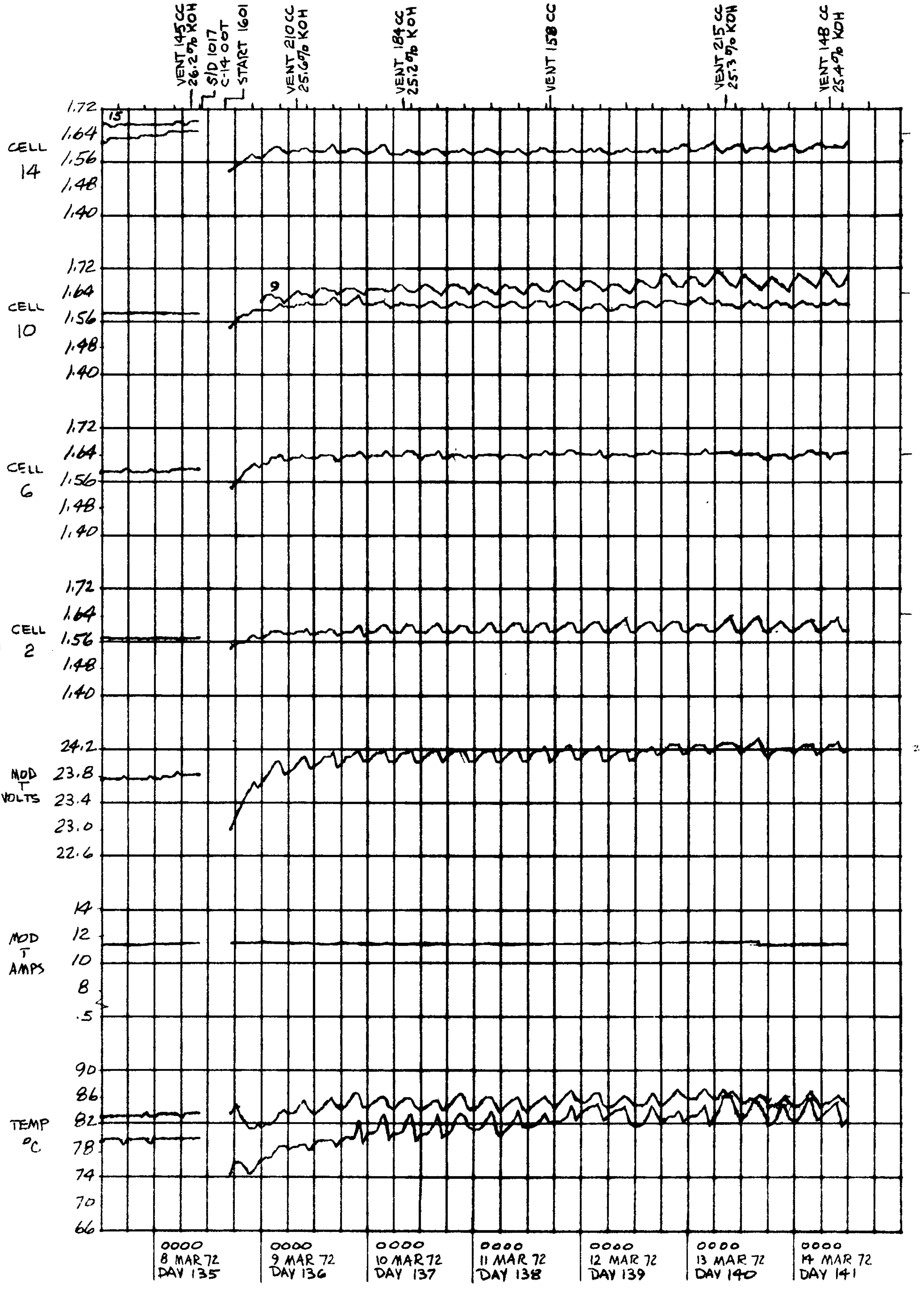


FIGURE 5-78 PERFORMANCE HISTORY (POSITION 2- MODULE 2)

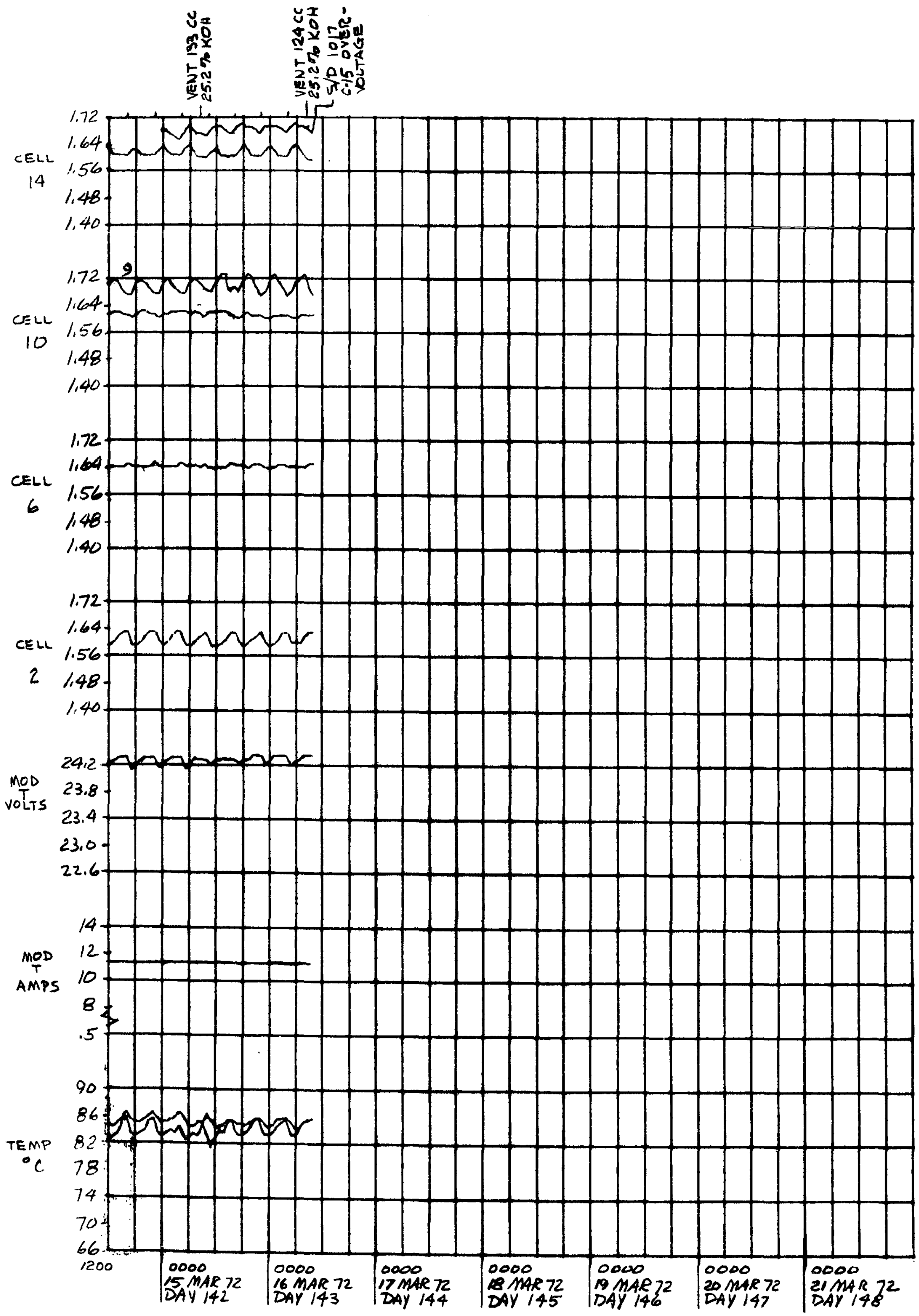
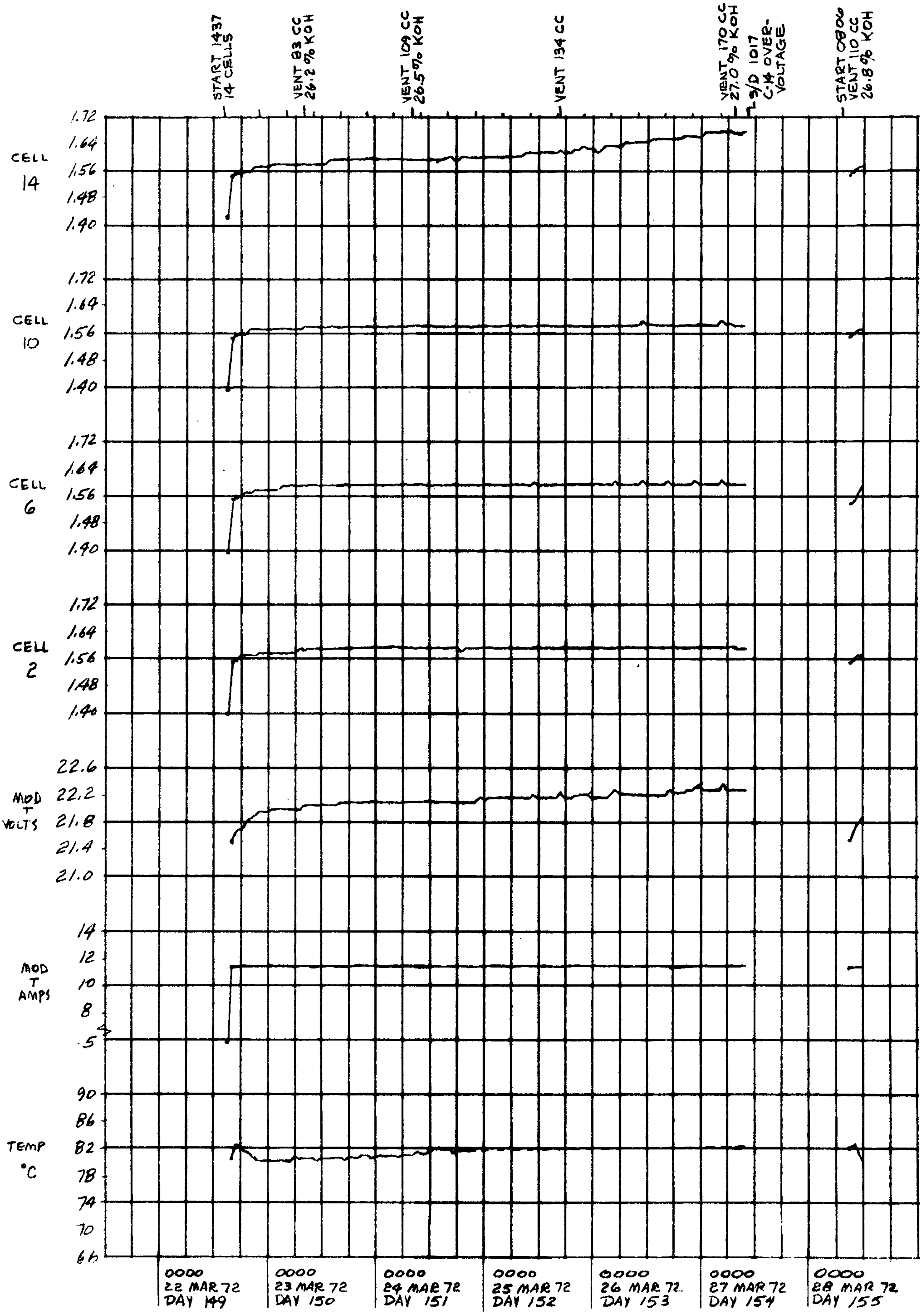


FIGURE 5-79 PERFORMANCE HISTORY (POSITION 2- MODULE 2)



The shutdown was caused by overvoltage in cell 14. The module was operating on only 14 cells at the time. The module was allowed to equilibrate for 6 hours and was then restarted at 1619. Evidently the equilization time was insufficient as the module ran only 6 hours and again cell 14 went overvoltage. This performance is shown on Figure 5-80. The module appeared in good condition and was therefore restarted at 1001 on 3 April after equalizing sine 2219 on 1 April, a period of 42 hours. The module then operated for about 3 days when a Dymec failure shut the entire system down at 1531 on 6 April. At the time of shutdown, cell 14's voltage was rising and would probably have gone out of tolerance in less than 24 hours. The module was removed from the system and inspected. The inspection revealed: a small amount of KOH on top of the module between cells 2 and 3 and a very small amount between cells 6 and 7, a small amount of KOH on lower heater tab at cells 2 and 3; KOH on electrode side between cells 2 and 3 screens, also at cell 6 and 7 interface, some KOH evident on bottom of module at cell 2 and 3 interface; very small amount of KOH on inlet H_2O tube fitting. Overall the module appeared in good condition with no operational defects requiring disassembly.

The module was then flushed, cell 15 reconnected electrically, and restarted at 1201 on 7 April. The performance of the module is shown on Figure 5-81. The next failure occurred at 1208 on 12 April when cell 9 went out-of-tolerance. Just prior to this failure the shutdown limits on cells 14 and 15 were raised from 1.75 to 1.80 volts. This was done to determine if there was a point at which cells 14 and 15 would level off at a new concentration condition or if the cell voltages would continue to rise. Cell 9 went out of tolerance instead. The module was again removed from the system and all cavities drained. The water cavity had only 80 cc's of liquid which indicated either some flooding had occurred between the 1208 shutdown and the 1430 draining or excess gas had been generated in the water cavities. Less than 3 cc's were found in the other two cavities. The module appeared in good condition with no external or cross leaks and was therefore flushed for one hour and restarted at 1647 on 12 April.

FIGURE 5-80 PERFORMANCE HISTORY (POSITION 2 - MODULE 2)

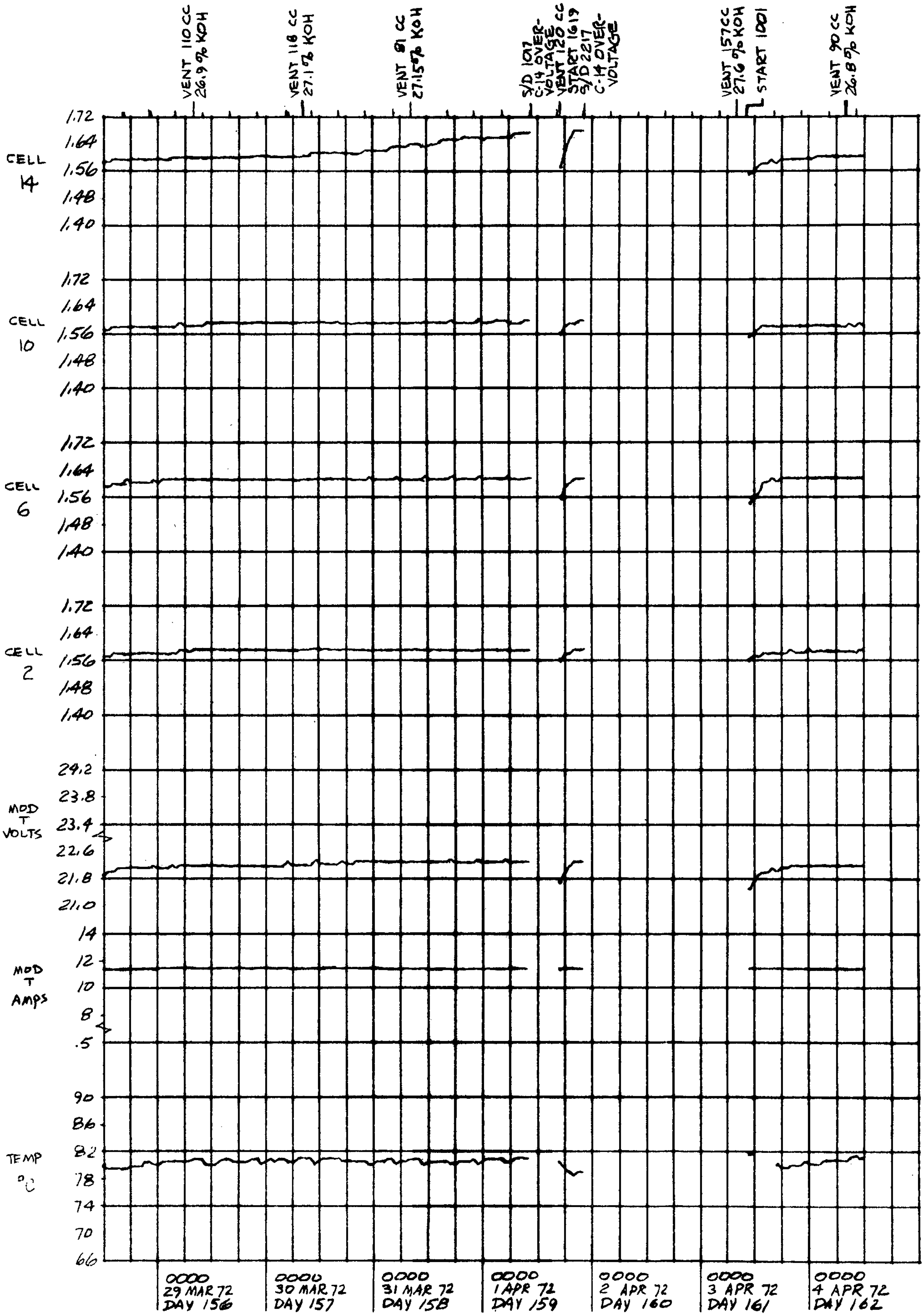
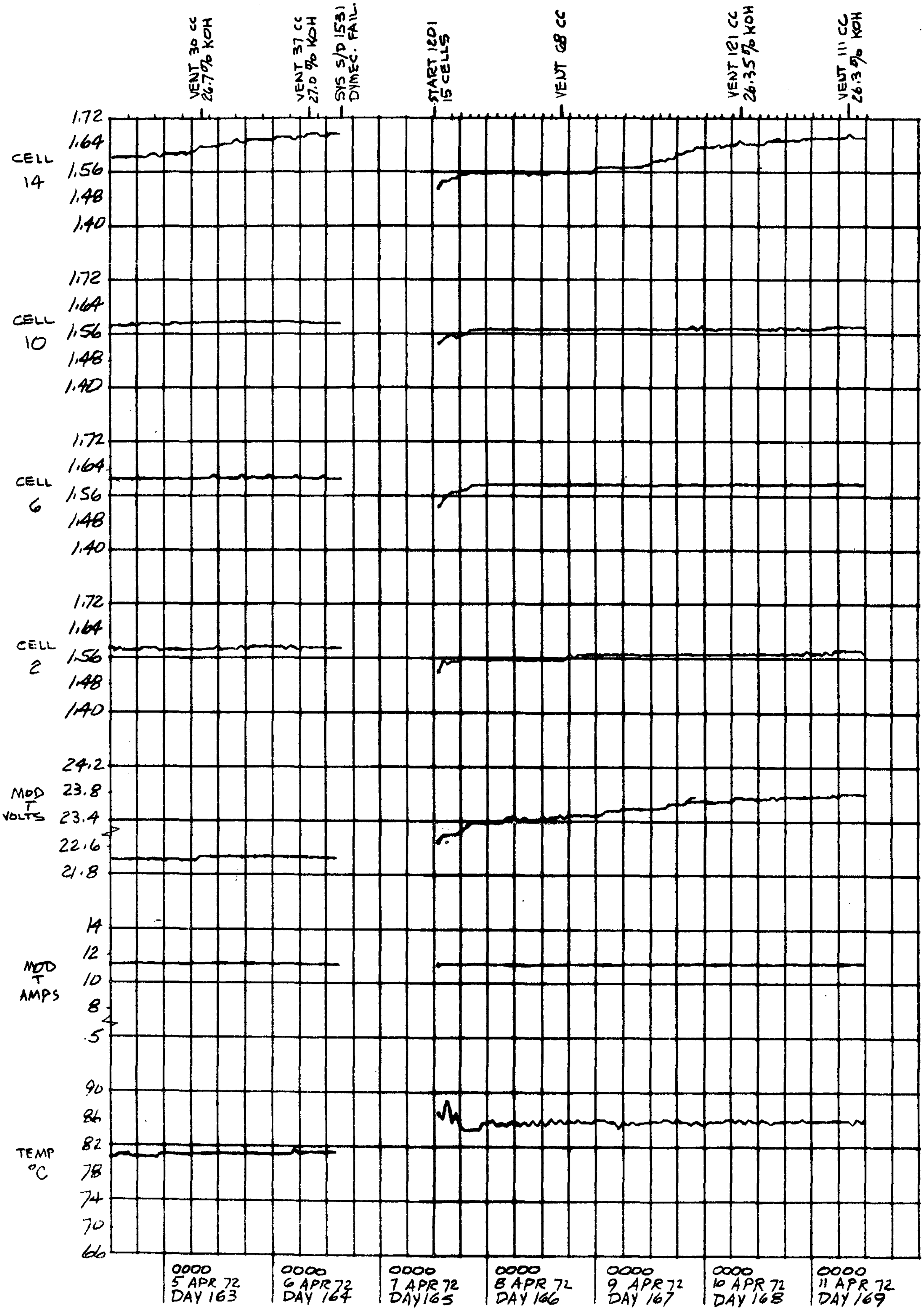


FIGURE 5-81 PERFORMANCE HISTORY (POSITION 2 - MODULE 2)



The module ran for less than 2 days and was shut down automatically by overvoltage in cell 9 at 0758 on 14 April. The two vent sequences performed during this period produced an exceptionally large quantity of gas - 444 cc's and 707 cc's. The performance of the module is shown in Figure 5-82. Figure 5-83 shows the cell voltage profiles that occurred each hour before shutdown on 12 April. As a result of the cell voltage profiles, the high gas rate and the two shutdowns indicated by cell 9, it was decided to disassemble the module. After removal from the system the module was drained, the H_2O cavity had 96 cc's liquid, O_2 and H_2 cavities had 4 cc's of liquid each. The visual inspection revealed: very little KOH on top of the module at cells 2 and 3, zero KOH on heater tab side of module, small quantity of KOH on H_2O inlet line fitting, small amount of KOH at bottom of electrode side at cells 1, 2 and 3, small amount of KOH on bottom of module at cells 1, 2 and 3 and also at cells 7, 8 and 9. In general, the module showed very little external leakage, and no visible damage. Crossleak check showed no leakage between H_2 and H_2O cavities and a leak rate of 4 bubbles per minute between the H_2 and O_2 cavities at a pressure differential of 2.75×10^4 N/m^2 gage (4 psig). There was no leak at a 2.06×10^4 N/m^2 (3 psig) differential. Cells 9 and 10 showed extensive contact between the electrolyte and heater wire. The plastic was burned. These two cells were replaced with good cells from module 1. The module was reassembled, tested, flushed and restarted at 1407 on 19 April and continued to operate with very uniform cell voltages until the end of the test period at 1200 on 25 April. Cell 15 was just beginning to show an upward trend at the time of final shutdown. Figure 5-84 shows the performance of the module for the last 6 test days. Thermocouple number 1 was used for temperature control at this time and due to the heat capacitance of the end plate and spacer plate the module experienced a delay in cell heater startup after circulation. The effect is shown on the figure as the small blips on each cell and on the module voltage curve.

FIGURE 5-82 PERFORMANCE HISTORY (POSITION 2 - MODULE 2)

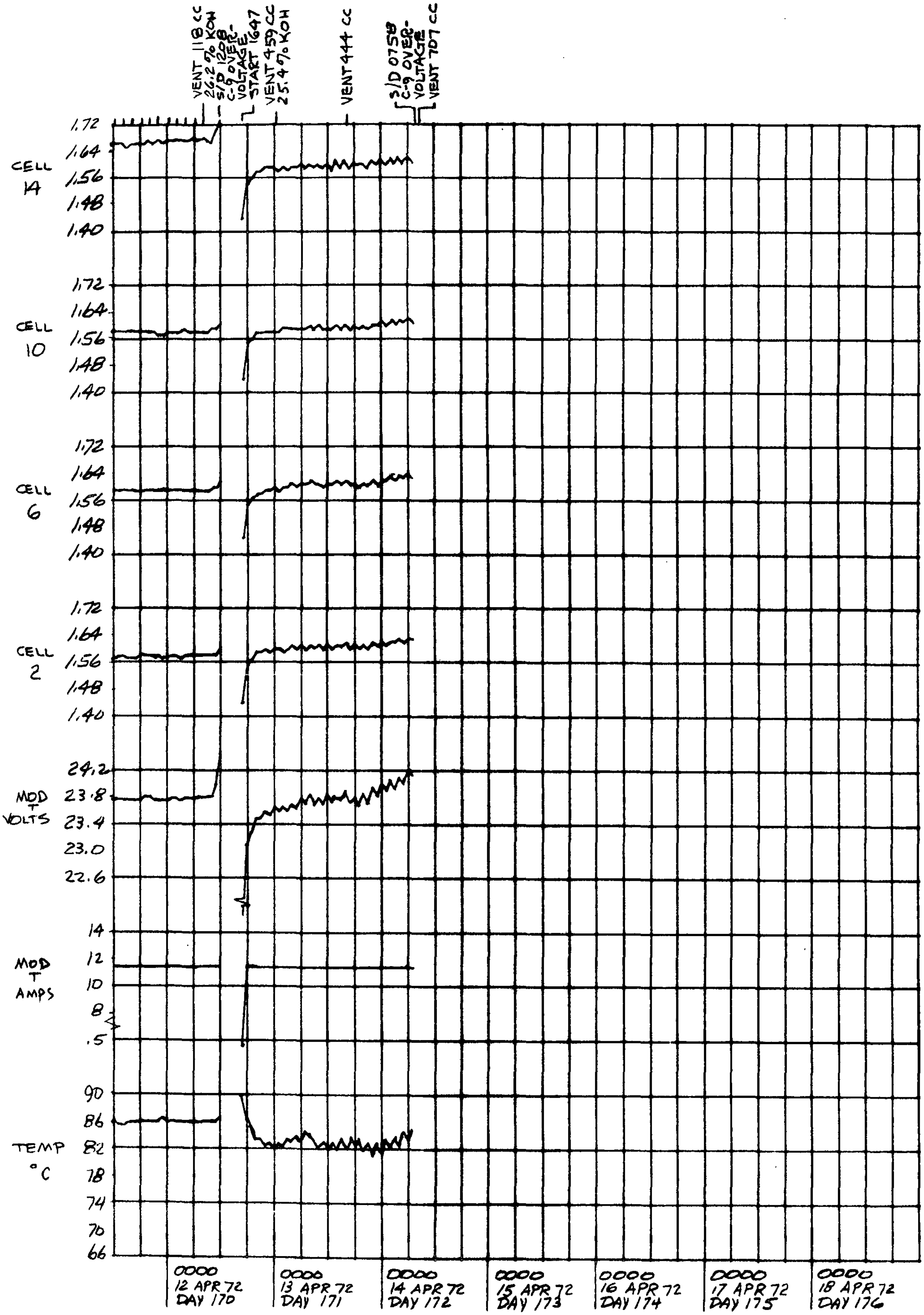


FIGURE 5-83 CELL VOLTAGE PROFILES
POSITION 2 MODULE 2

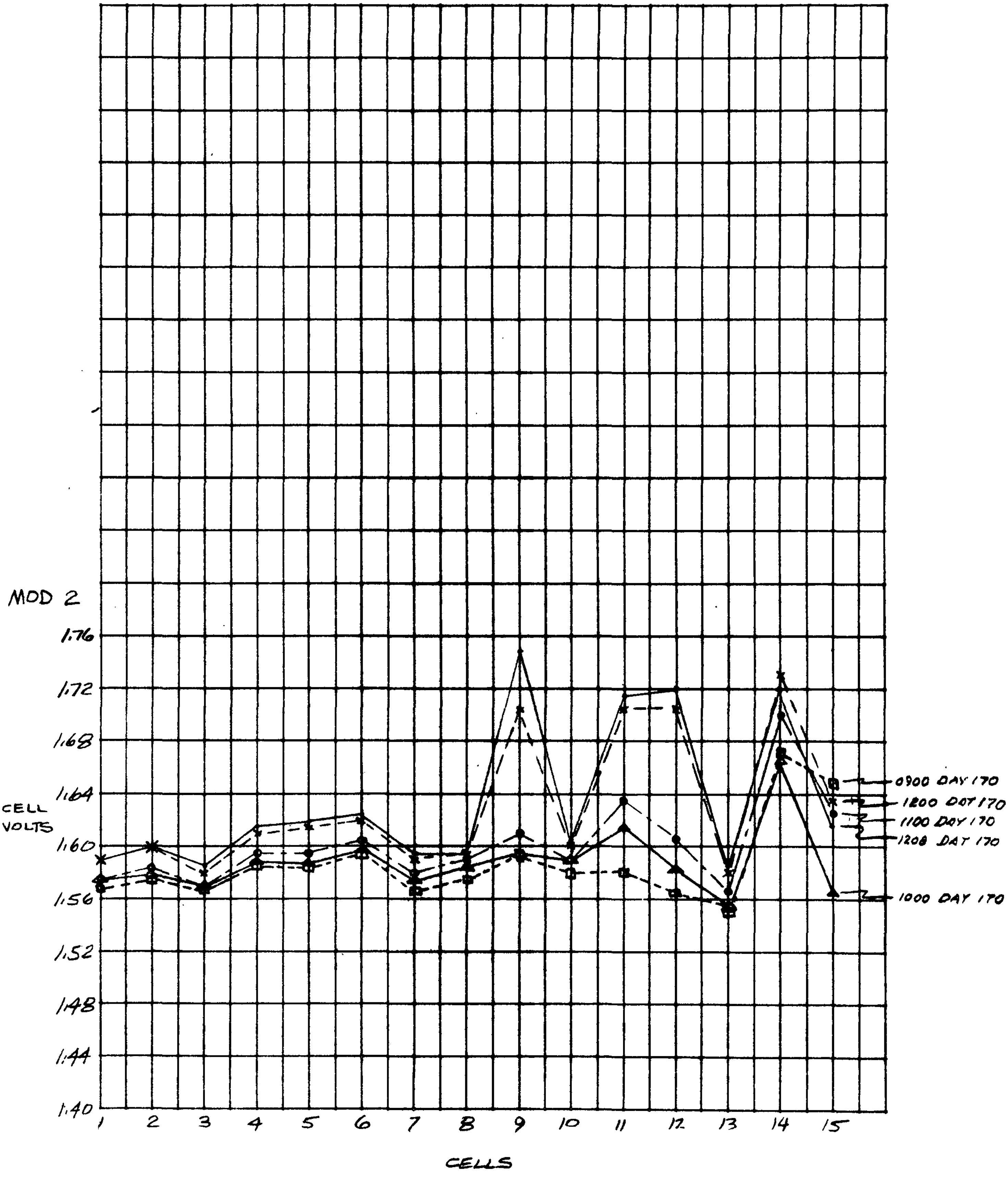
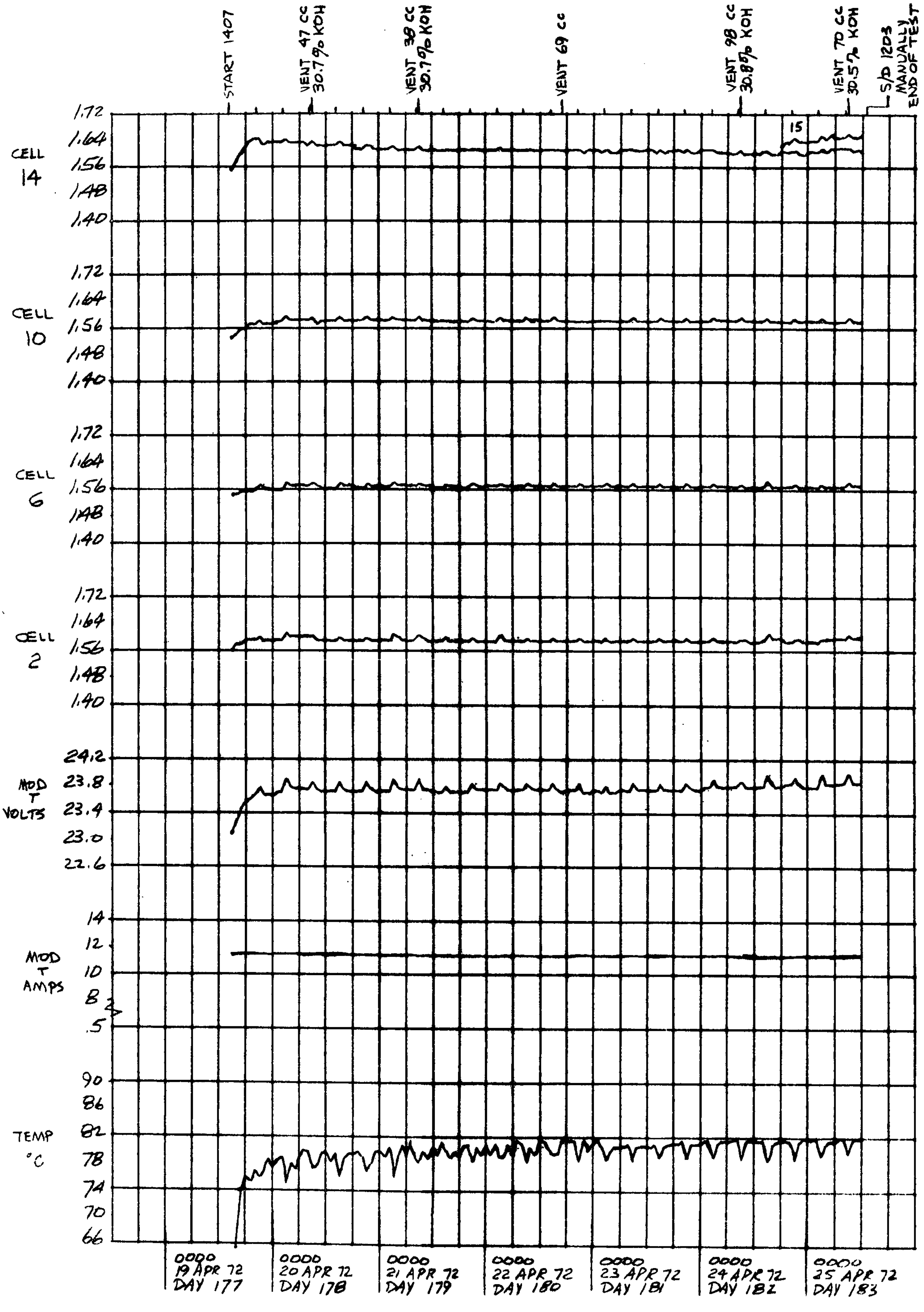


FIGURE 5-84 PERFORMANCE HISTORY (POSITION 2-MODULE 2)



5.7.2.3 Module 3

Figure 5-85 through 5-92 show the detailed performance of this module during the 21 October through 2 November performance period. The system shutdown between 0800 and 1600 on 22 October 1971 was required to repair a facility cooling water booster pump. Subsequent to this shutdown module 3 experienced three shutdowns, all from overvoltage in cell 1 and/or cell 5. In each case the module had operated less than 14 hours before failure. After the first shutdown the system concentration was determined to be 25.7%. No measurement was taken after the second shutdown. After the third shutdown the concentration was 27.2%.

Figure 5-93 shows a minute-to-minute change in the conditions of cells 1, 2 and 14 in this module. Cell 1 caused the shutdown by overvoltage at 0246. It is apparent from the curve that the circulation start at 0243 precipitated the module and cell voltage raise. Temperature changes within this module were less than 2°K (3.6°F) during the period of the circulation. No other changes to the system occurred at this time.

After a 6-hour flush on the flush cart, the concentration in the flush cart had risen from 30.2 to 30.8%. Distilled water was added to the flush cart to reduce the concentration to the 30.0 to 30.5% range and the module flushed for an additional hour. The module was then operated for 24 hours at 11.3 amperes. A concentration check during the period indicated that the system concentration was 23.8%. After 24 hours of operation at nearly steady conditions, the test committee directed that the amperage level on this module be reduced to 5.5 amperes. On 1 November the current was increased to 8.0 amperes. The 66 hours at 5.5 amperes was very steady with no significant or unexpected changes in performance. Analog control was initiated at 1200 on 2 November making it difficult to monitor trends in performance until the end of analog control operation on 9 November.

FIGURE 5-85 PERFORMANCE HISTORY (POSITION 2- MODULE 3)

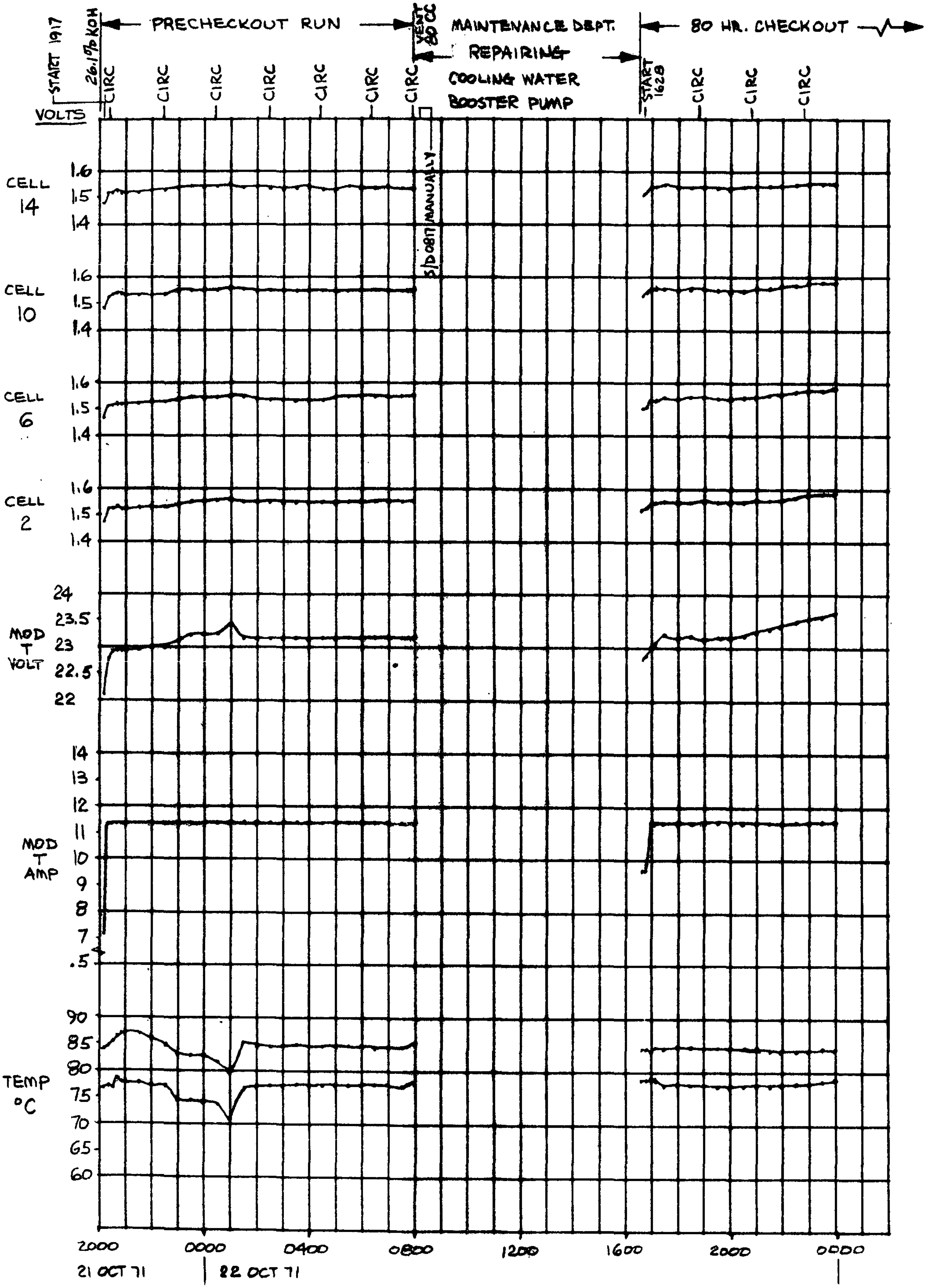


FIGURE 5-86 PERFORMANCE HISTORY (POSITION 2 - MODULE 3)

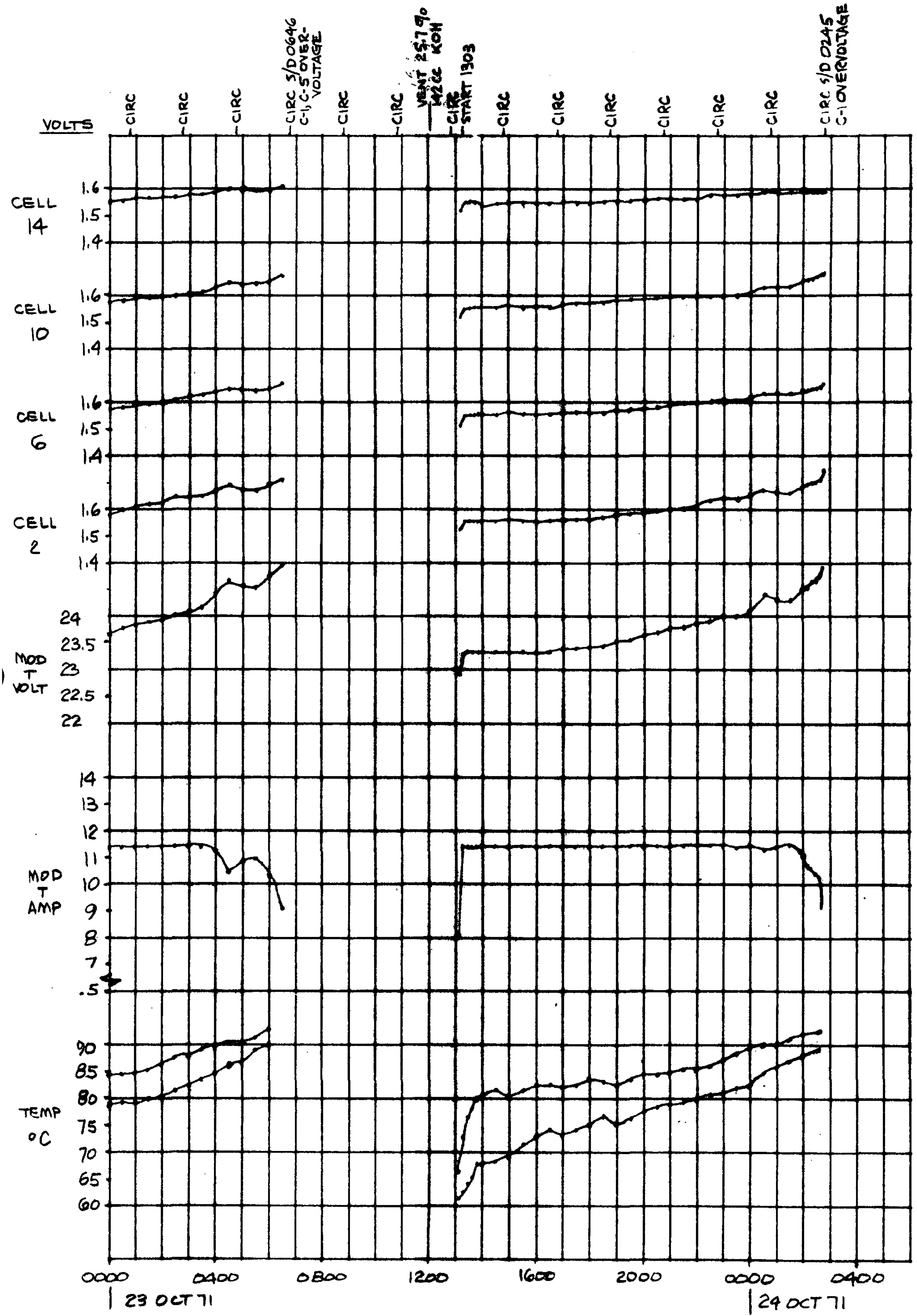


FIGURE 5-87 PERFORMANCE HISTORY (POSITION 2-MODULE 3)

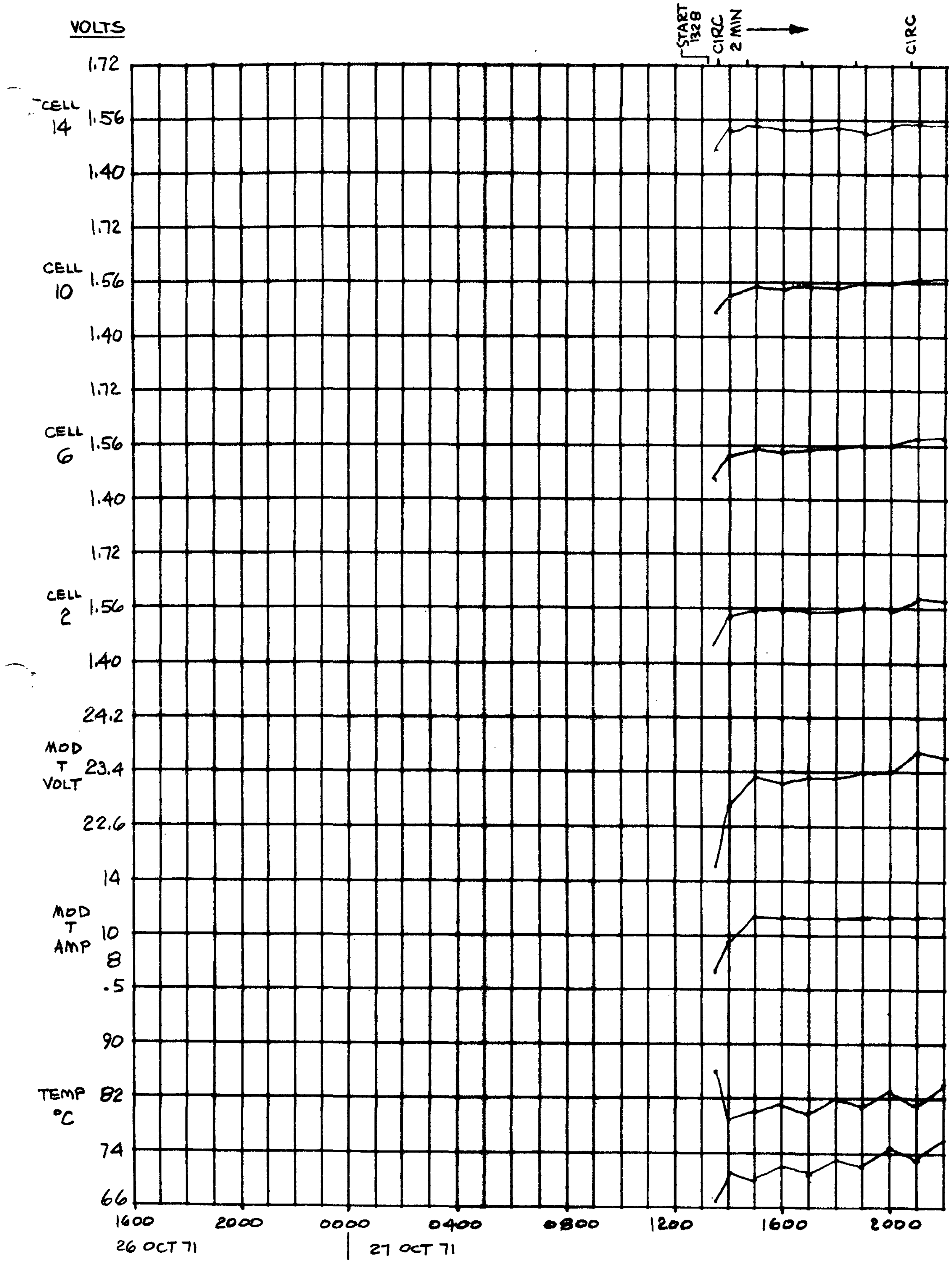


FIGURE 5-88 PERFORMANCE HISTORY

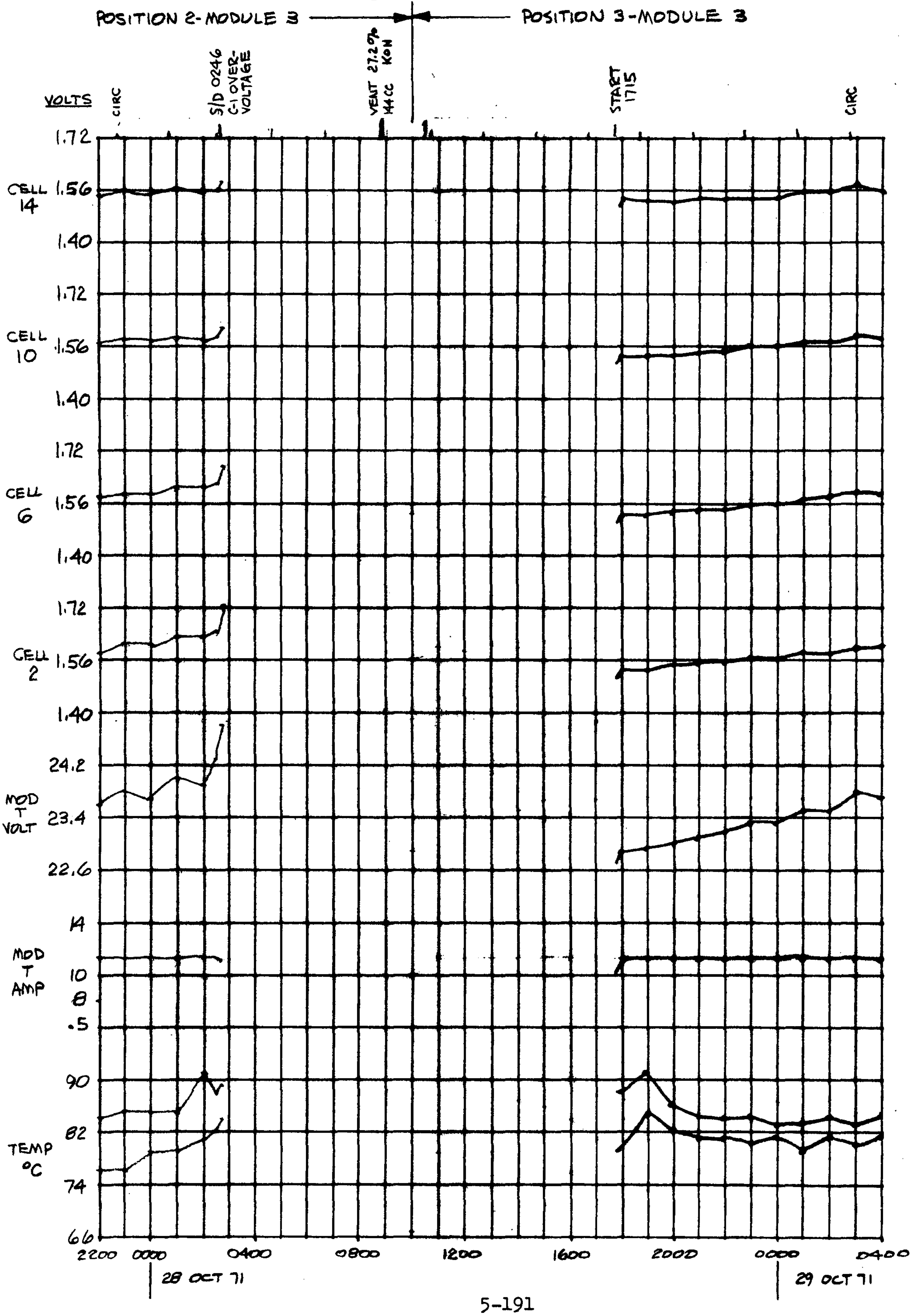


FIGURE 5-89 PERFORMANCE HISTORY (POSITION 3- MODULE 3)

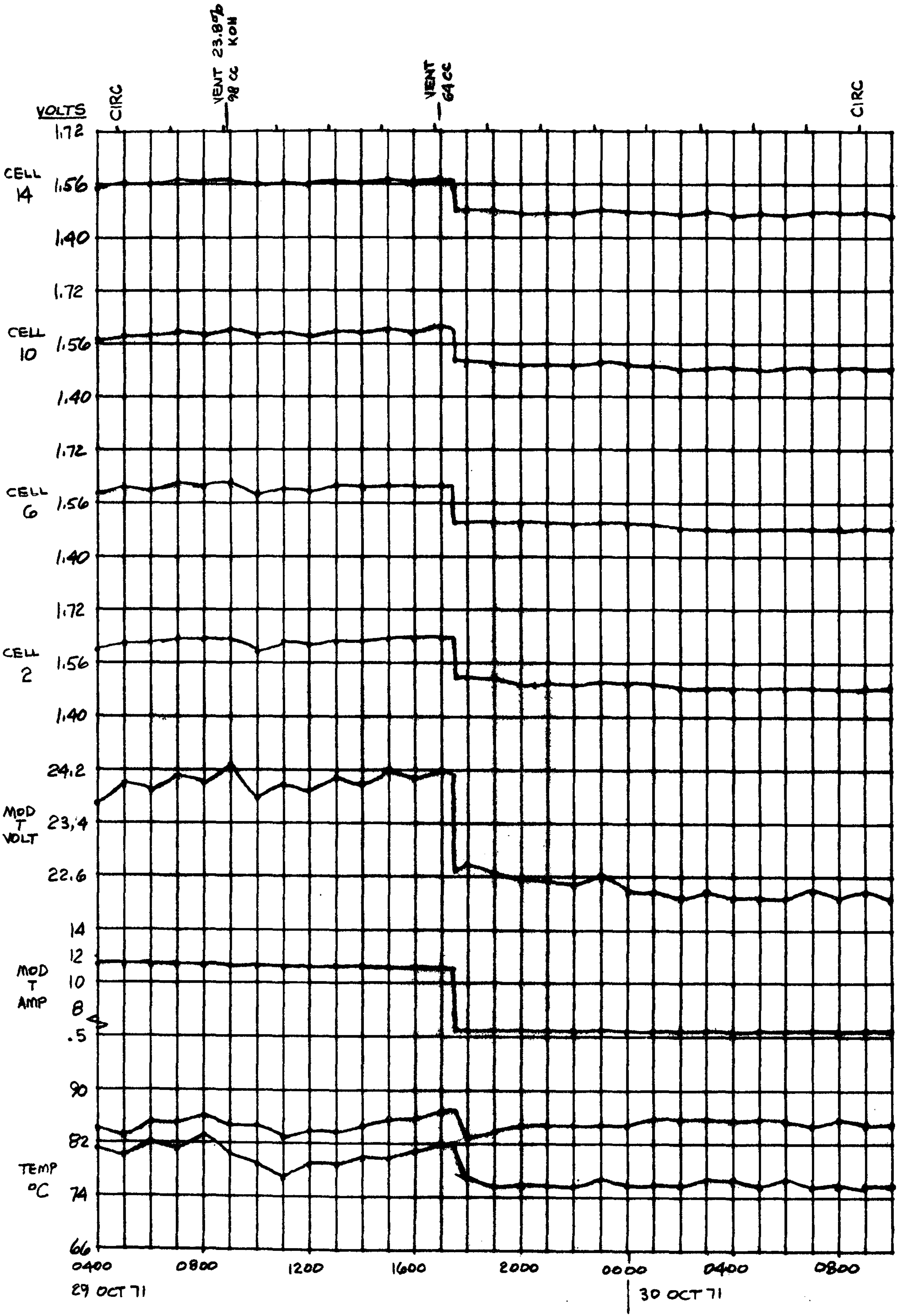


FIGURE 5-90 PERFORMANCE HISTORY (POSITION 3-MODULE 3)

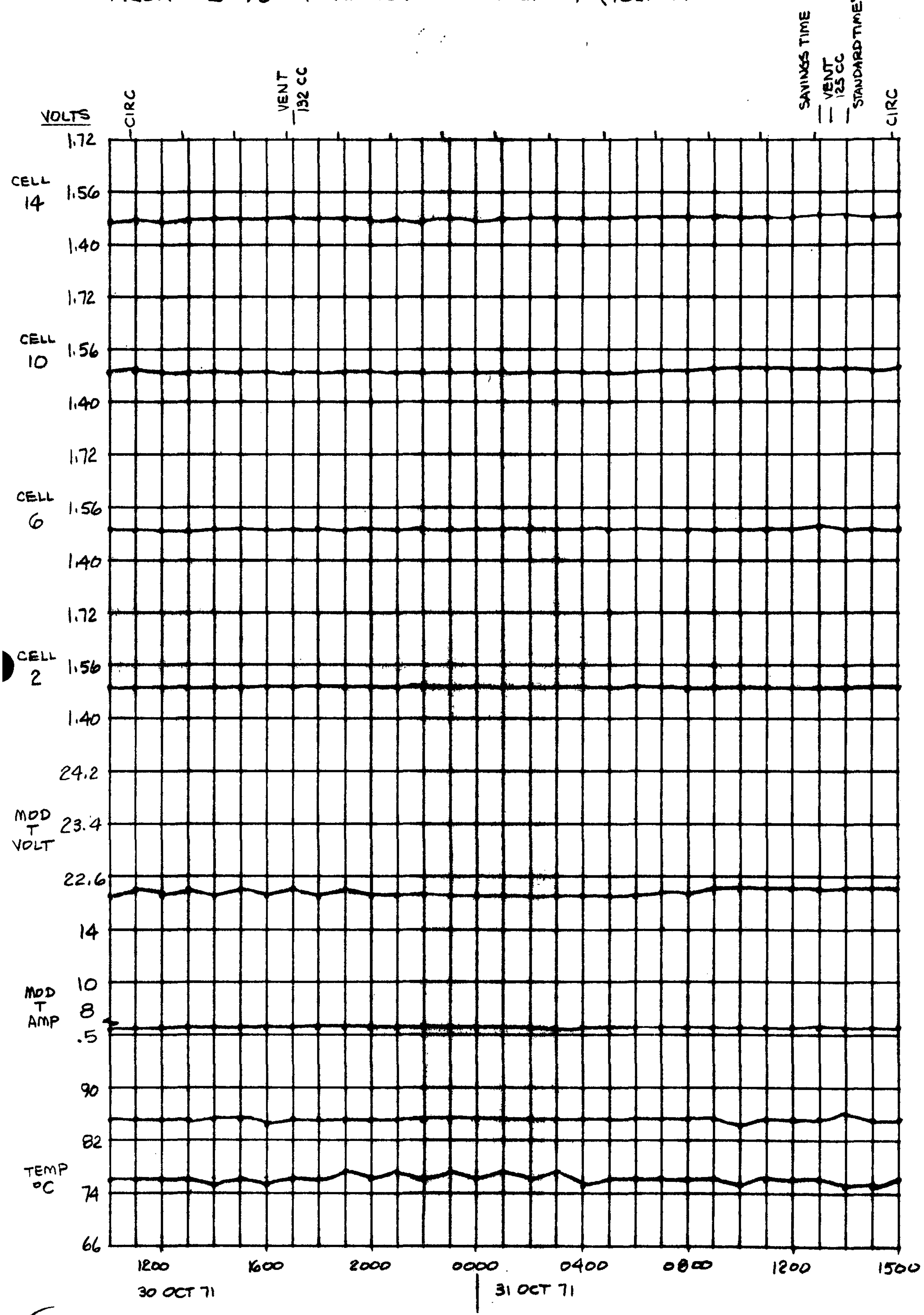


FIGURE 5-91 PERFORMANCE HISTORY (POSITION 3-MODULE 3)

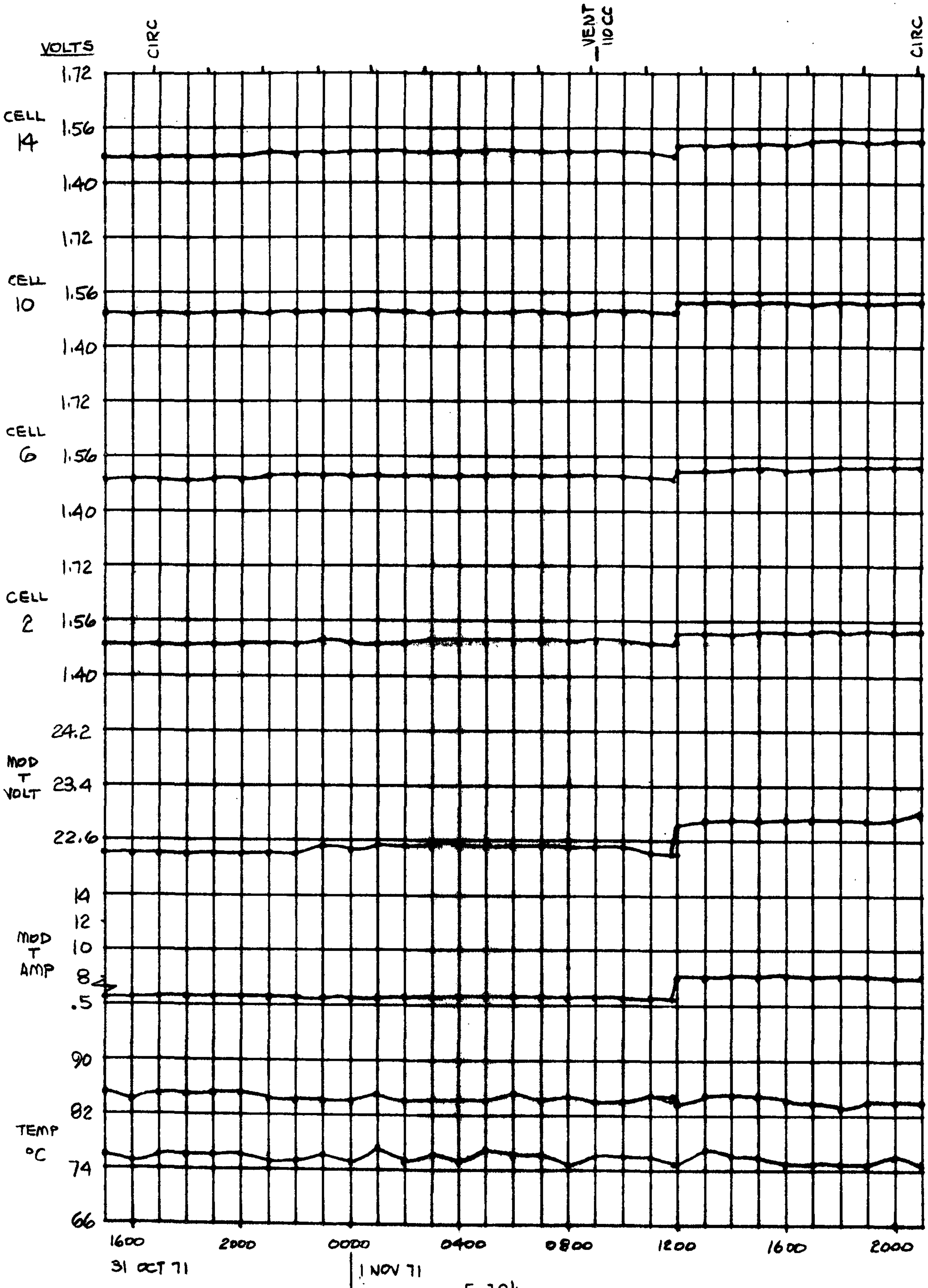


FIGURE 5-92 PERFORMANCE HISTORY (POSITION 3 - MODULE 3)

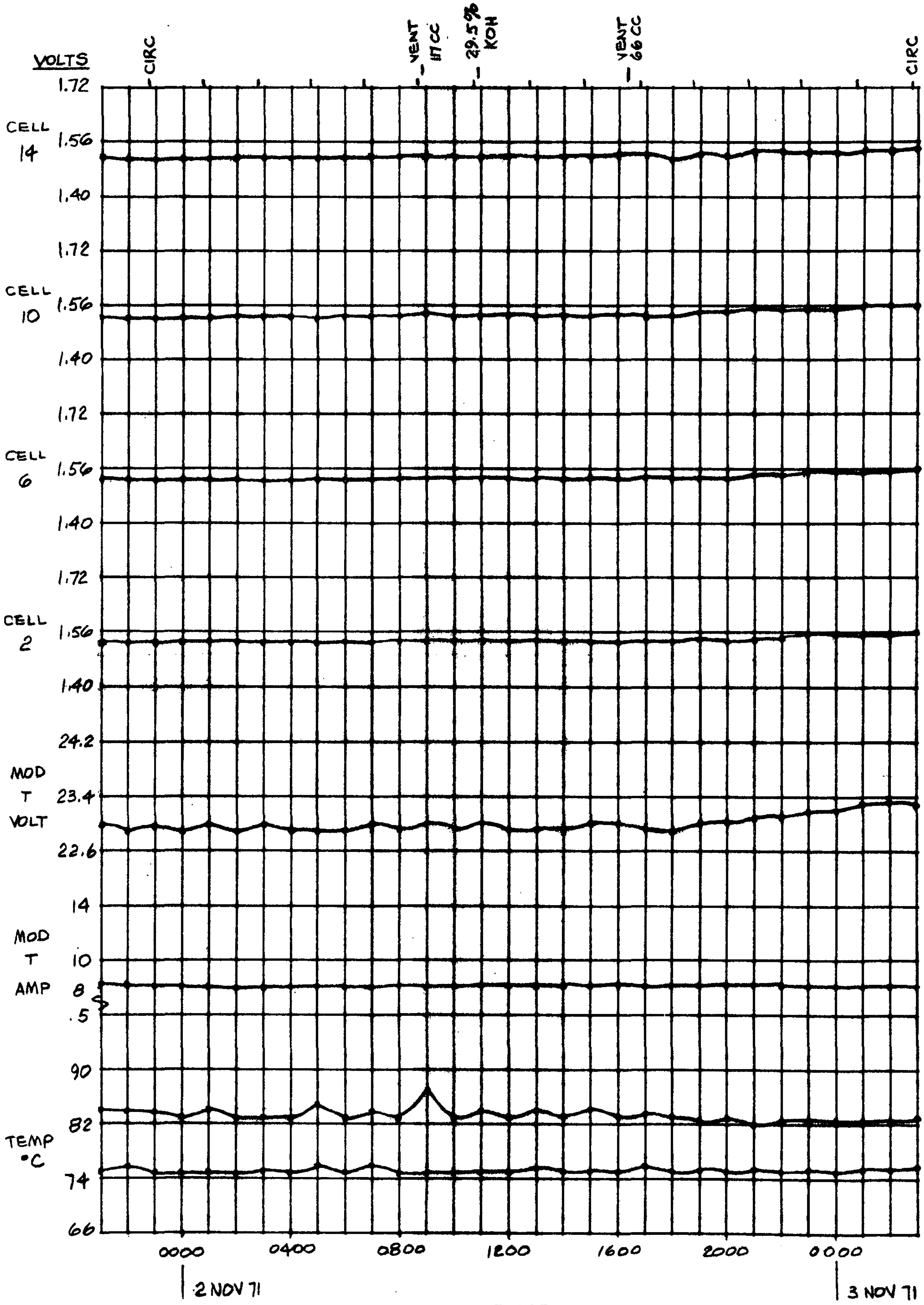
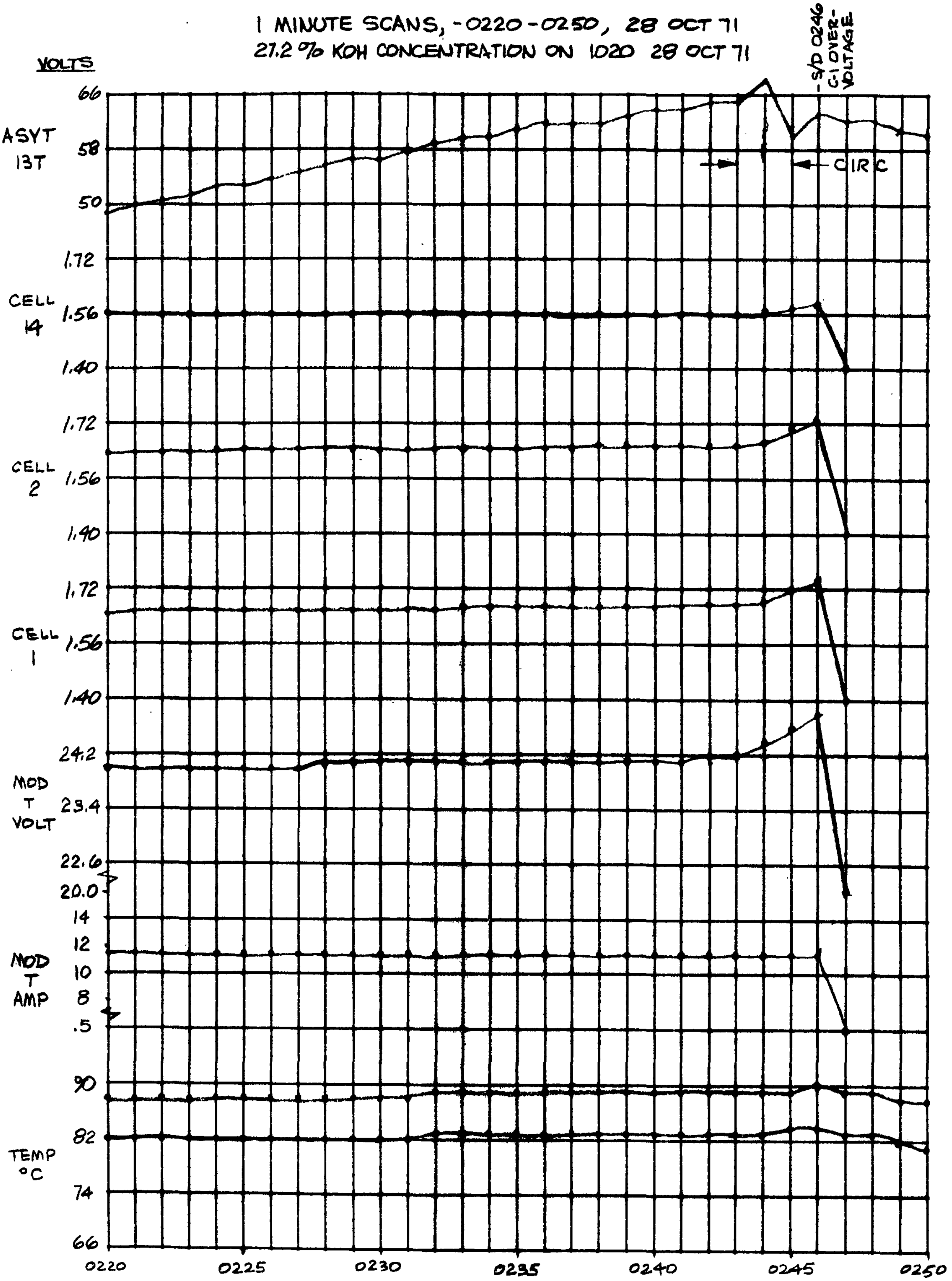


FIGURE 5-93 PERFORMANCE HISTORY (POSITION 2- MODULE 3)



1 MINUTE SCANS, -0220-0250, 28 OCT 71
27.2% KOH CONCENTRATION ON 1020 28 OCT 71

Figures 5-94 through 5-98 show the performance history of the module during the analog control period of operation. During this period the module was operated at an average current of 8 amperes. As before, a gradual increase in module and cell voltages is evident until failure occurred at 0047 on 9 November 1971 due to overvoltage in cell 2. All major peaks on the module voltage curve can be correlated to the electrolyte circulation cycle and/or venting of the separator. After removing this module from the system it was placed on the flush cart and flushed for 18 hours. Initial KOH concentration in the flush cart was 30.5%; final concentration was 30.9% KOH, thus indicating very little KOH buildup in this module during 271 hours of continuous operation at an average of 8 amperes.

The module operated very uniformly after restarting at 1133 on 16 December, as shown in Figure 5-99, until the system was shut down at 2046 on 19 December. The module was then removed from the system and all cavities drained and samples analyzed. The results are as follows:

H_2O Cavity	147 cc's	28.2%
H_2 Cavity	26.4 cc's	28.7%
O_2 Cavity	5.8 cc's	24.0%

This data indicates that, during the 14 hours of waiting before draining, the module partially equalized and some minor flooding occurred. With zero pressure differentials the flooding liquid tended to collect in the H_2 cavity rather than be forced into the O_2 cavity. The module was flushed and prepared for reuse in the system.

Restart occurred at 0906 on 23 December and at 1646 the total system shutdown due to an out-of-tolerance differential pressure switch setting. The module was restarted at 1150 23 December (Figure 5-100) and operated until 0815 the following day at which time an overvoltage condition occurred in cells 1 and 2. The module was removed and drained. The water cavity contained 134 cc's of 31.8% KOH. There was no

FIGURE 5-94 PERFORMANCE HISTORY (POSITION 3-MODULE 3)

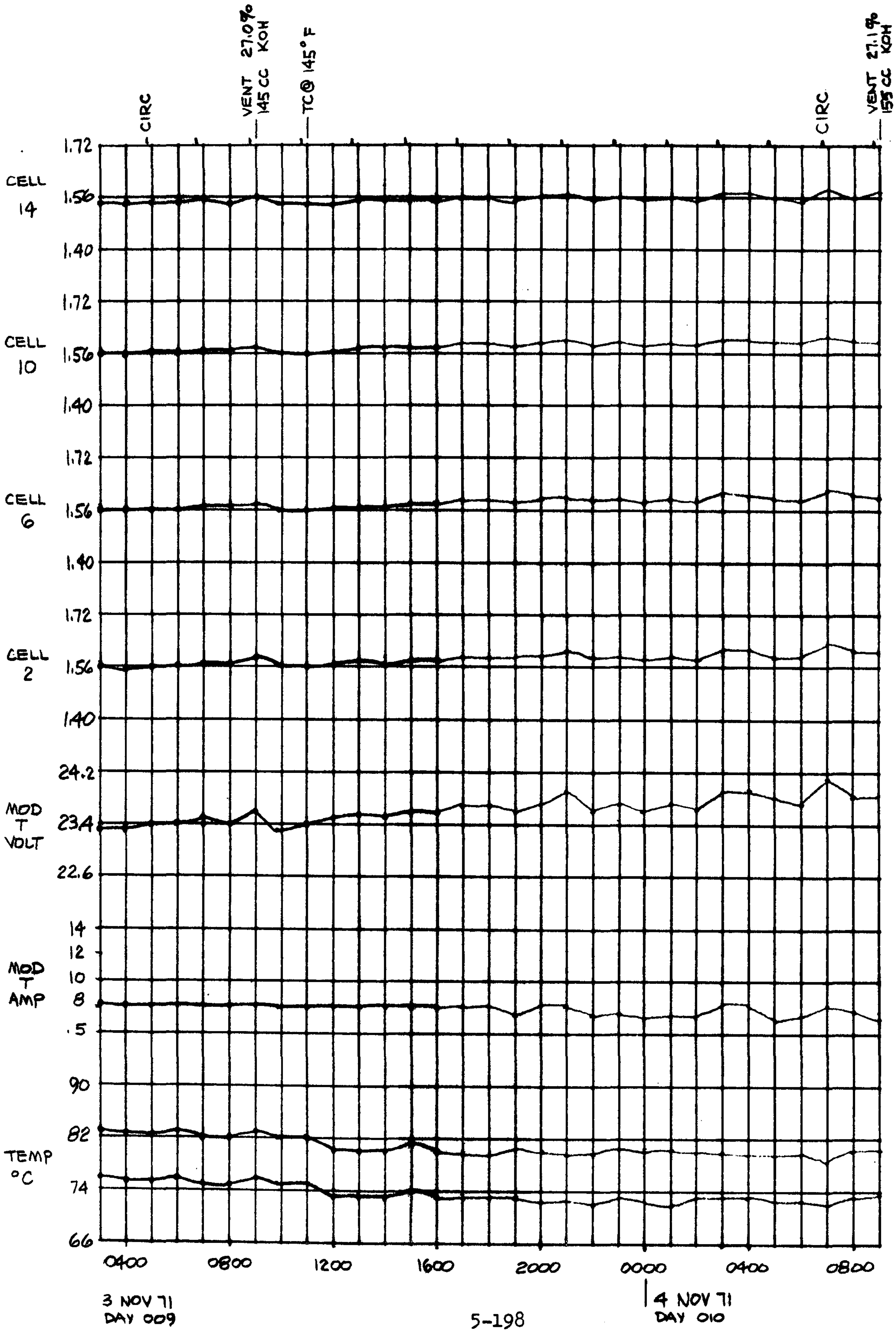


FIGURE 5-95 PERFORMANCE HISTORY (POSITION 3- MODULE 3)

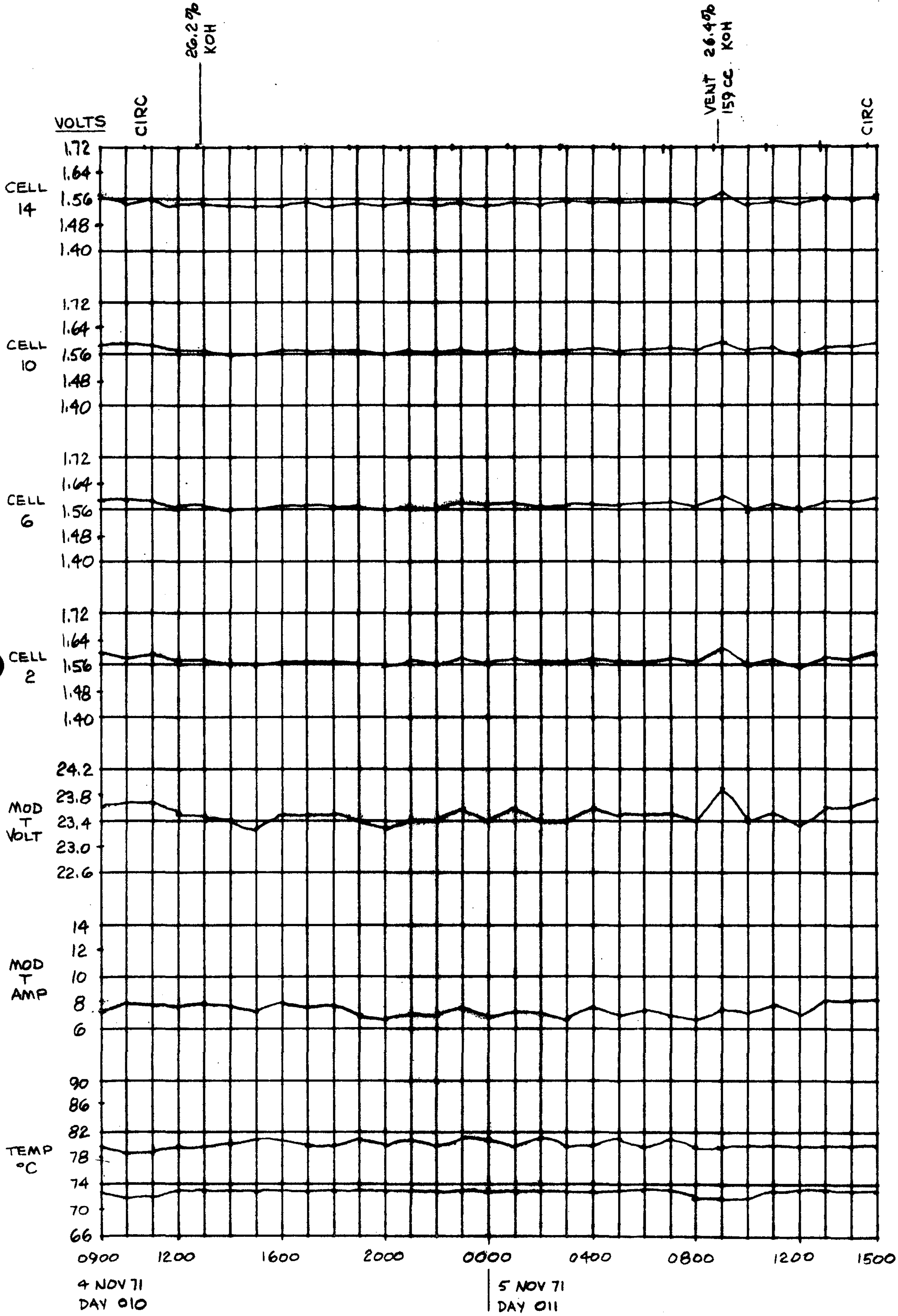


FIGURE 5-96 PERFORMANCE HISTORY (POSITION 3- MODULE 3)

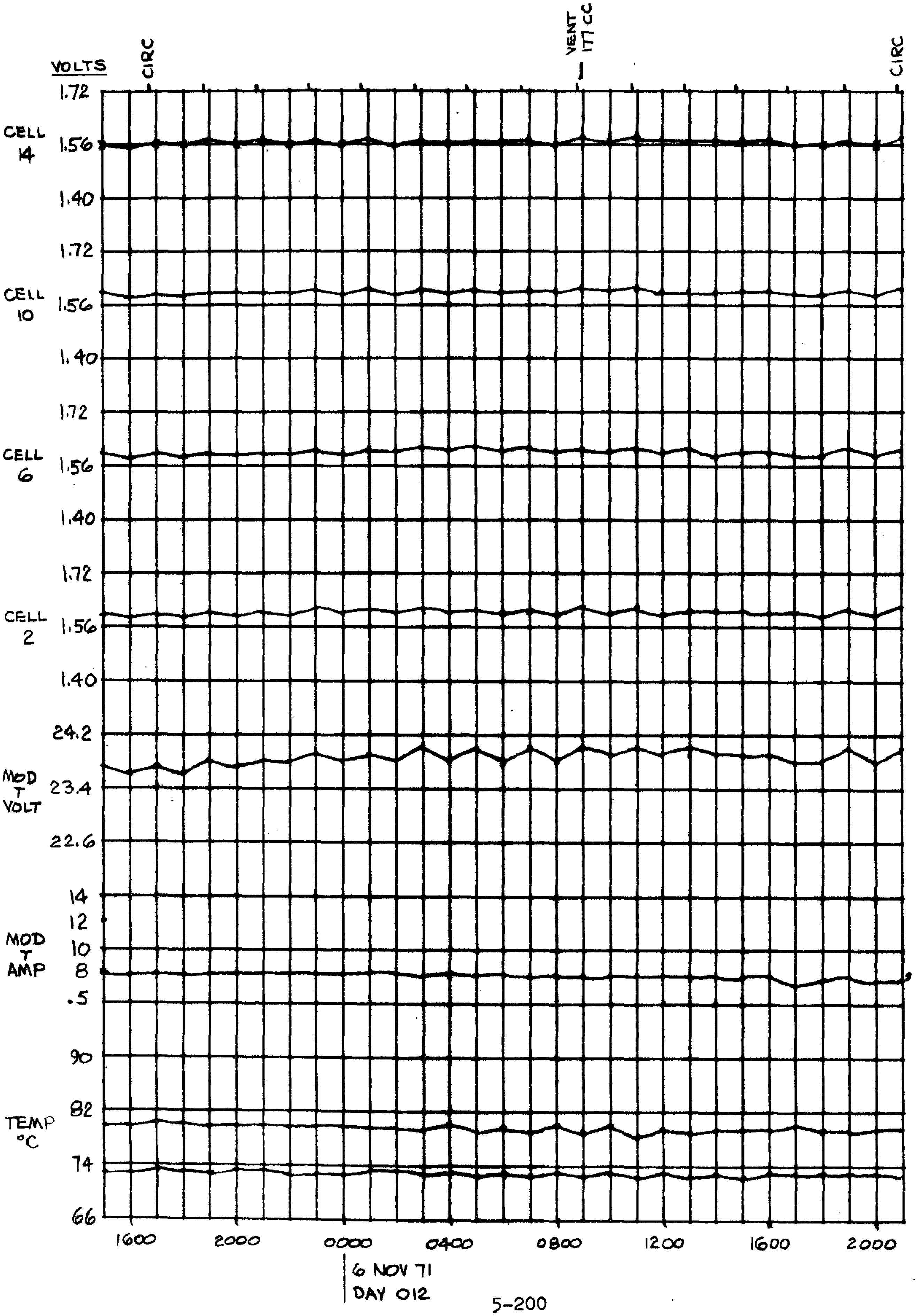


FIGURE 5-97 PERFORMANCE HISTORY (POSITION 3 - MODULE 3)

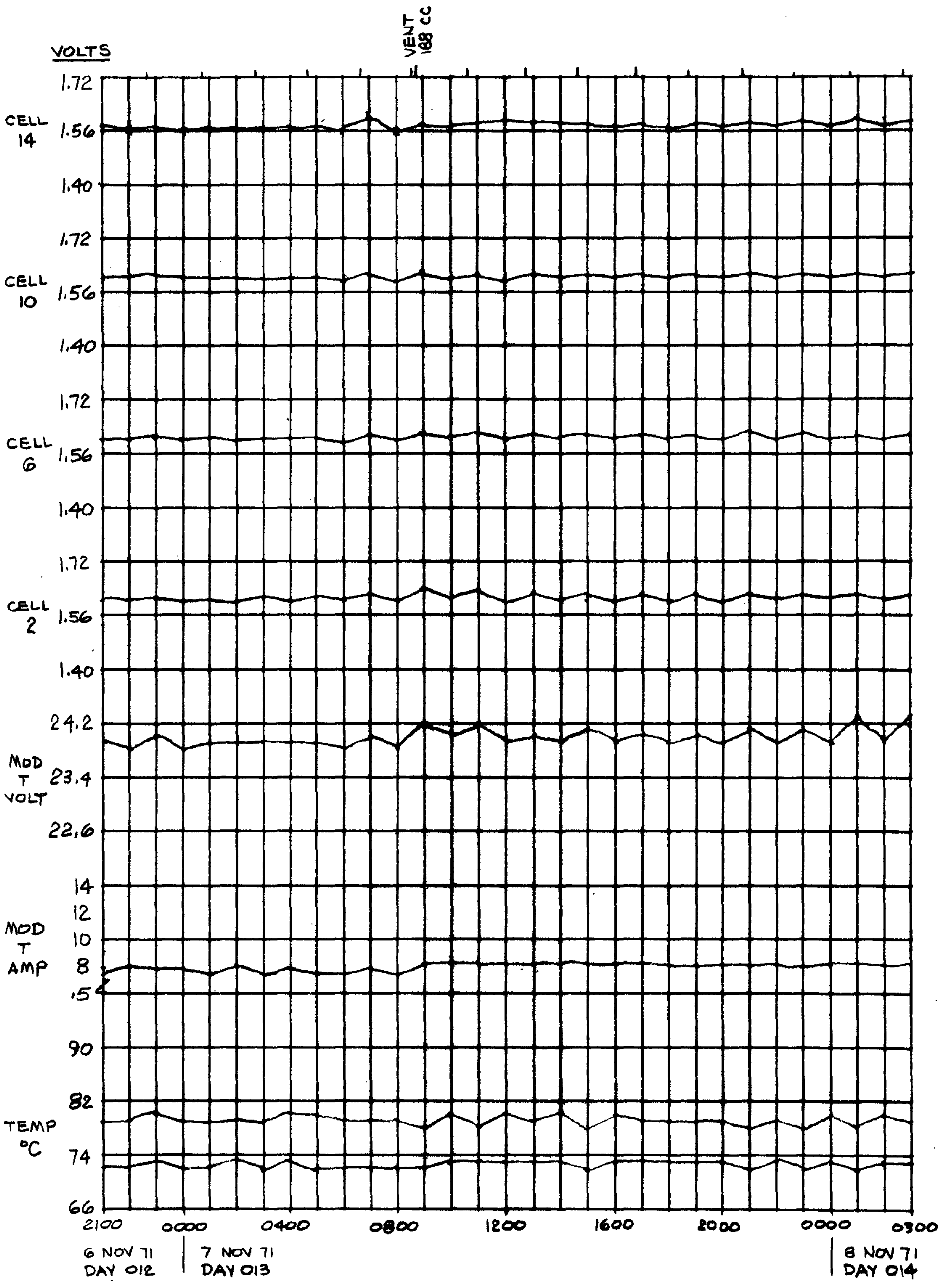


FIGURE 5-98 PERFORMANCE HISTORY (POSITION 3 - MODULE 3)

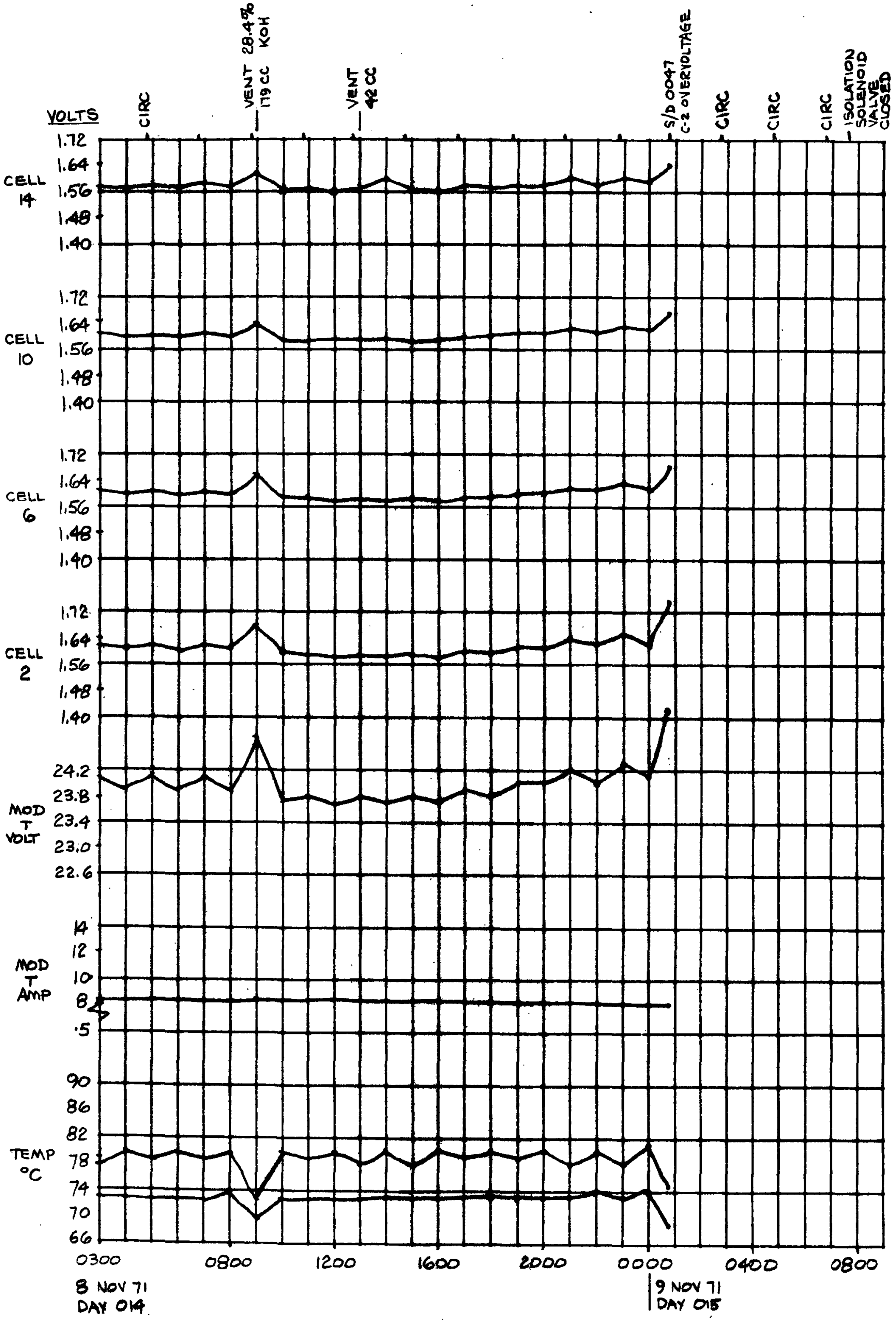


FIGURE 5-99 PERFORMANCE HISTORY (POSITION 3 - MODULE 3)

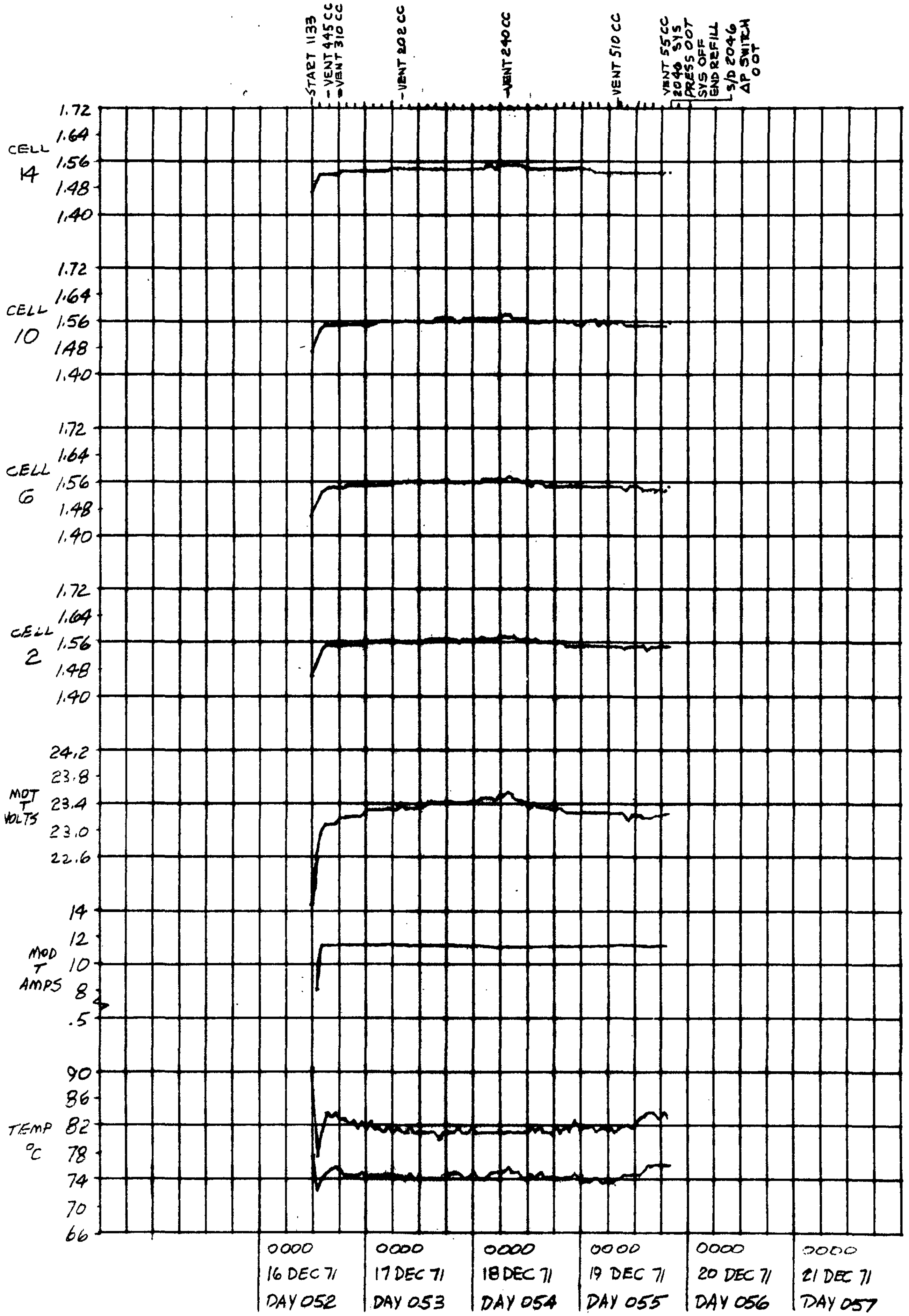
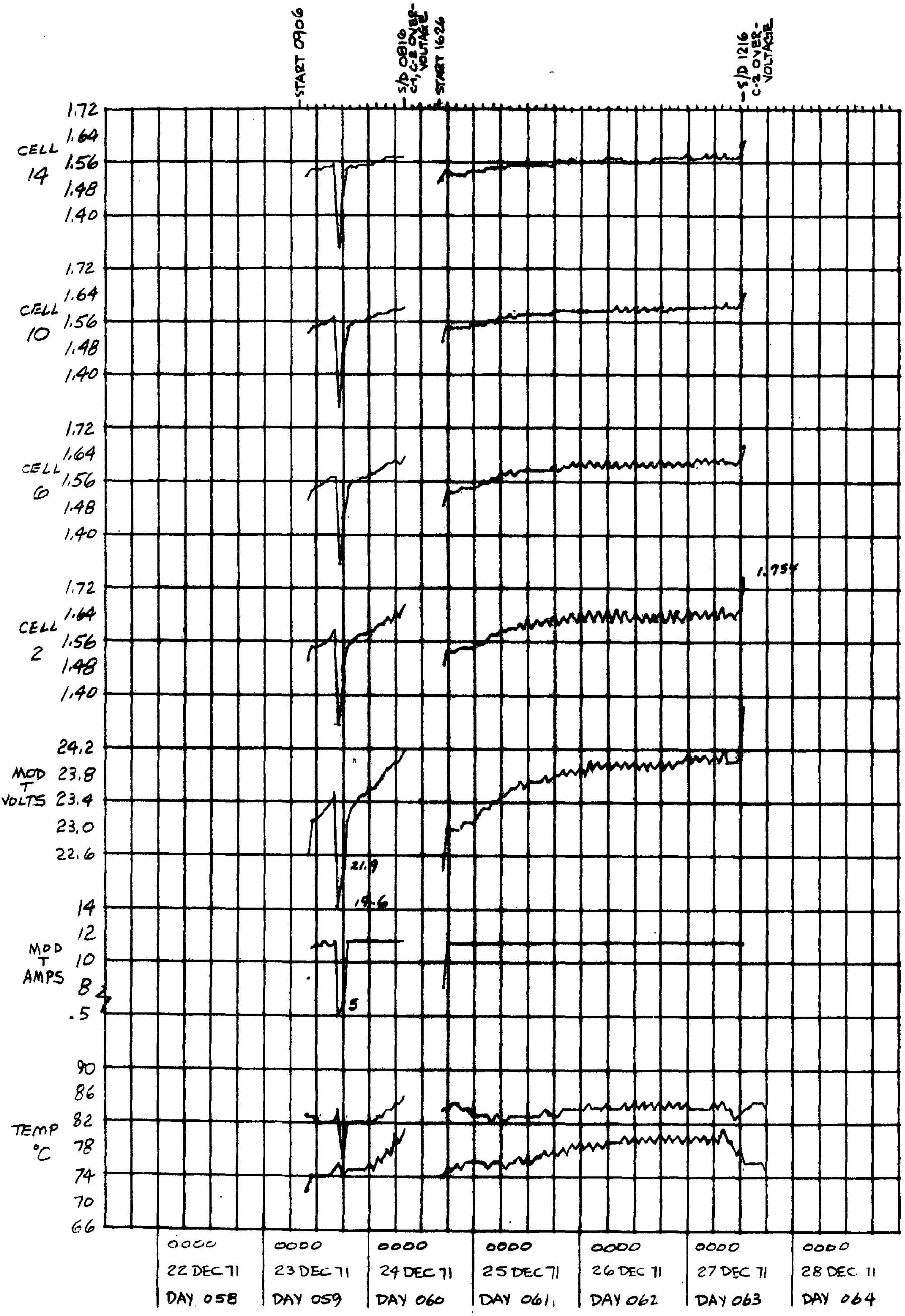


FIGURE 5-100 PERFORMANCE HISTORY (POSITION 3- MODULE 3)



liquid in either the H_2 or O_2 cavities. The module was drained within one hour of shutdown and was not subjected to any circulations subsequent to shutdown. Electrolyte loop concentation was 24.5% at the time. The high water cavity concentration just after a circulation indicates KOH collecting in the water matrix. The module was reflushed, one cavity at a time; the results are as follows:

Cavity	Flush Cart Concentration Initial	Final
H_2O	30.7%	30.6%
H_2	29.6%	30.7%
O_2	30.6%	30.6%

Electrode screens were resoldered in a few places due to what appeared to be poor connections. The module was restarted at 1626 on 24 December and continued to operate until 1216 on 27 December. Figure 5-100 shows the performance of this module for the two periods.

On 28 December the module was removed from the system and drained. Quantities of liquids collected and the concentration of each sample is shown below as are initial and final concentrations in the flush cart as each cavity was flushed:

Cavity	Liquid Quantity Collected	Sample Concentration	Flush Cart Concentration Initial	Final
H_2O	146	21.4%	28.7%	28.7%
H_2	Zero		30.2%	28.7%
O_2	62	23.4%	28.7%	28.7%

It should be noted that this module was subjected to 10 circulations prior to isolation and 21 hours of sitting prior to cavity sample collection, thus the value of the concentration information is questionable. Flooding did occur as evidenced by the 62 cc's of liquid collected from the O_2 cavity. Pressure differentials were maintained within the module for 21 hours after module shutdown.

Figures 5-101 through 5-103 show the conditions in the worst cells 8 hours and 2 hours before shutdown again indicating that KOH buildup in the water matrices is a long term process. In each succeeding circulation the cell voltages were slightly higher than the preceeding circulation, until finally an out-of-tolerance condition existed and the module was shutdown. The cause of the temperature crossover plotted on Figures 5-102 and 5-103 was not determined. External inspection of the module indicated the module was ready to be installed in the system and reused when proper electrolyte concentrations in the matrices was accomplished.

The module was restarted at 1402 on 11 January and operated until 0446 on 13 January at which time cell 12 went out of tolerance (see Figure 5-104). The module was removed from the system at 0830 on 13 January and all cavities drained and the samples analyzed. The results are as follows:

H_2O Cavity	97 cc liquid	36.8% KOH
H_2 cavity	zero liquid	----
O_2 cavity	3.2 cc liquid	27.6% KOH

The system concentration at this time was 22.5% KOH. The module had been off about 4 hours before removal from the system and had been subjected to one circulation after shutdown. Each cavity of the module was flushed separately, the results were as follows:

FIGURE 5-101 CIRCULATION EFFECT (POSITION 3 - MODULE 3)

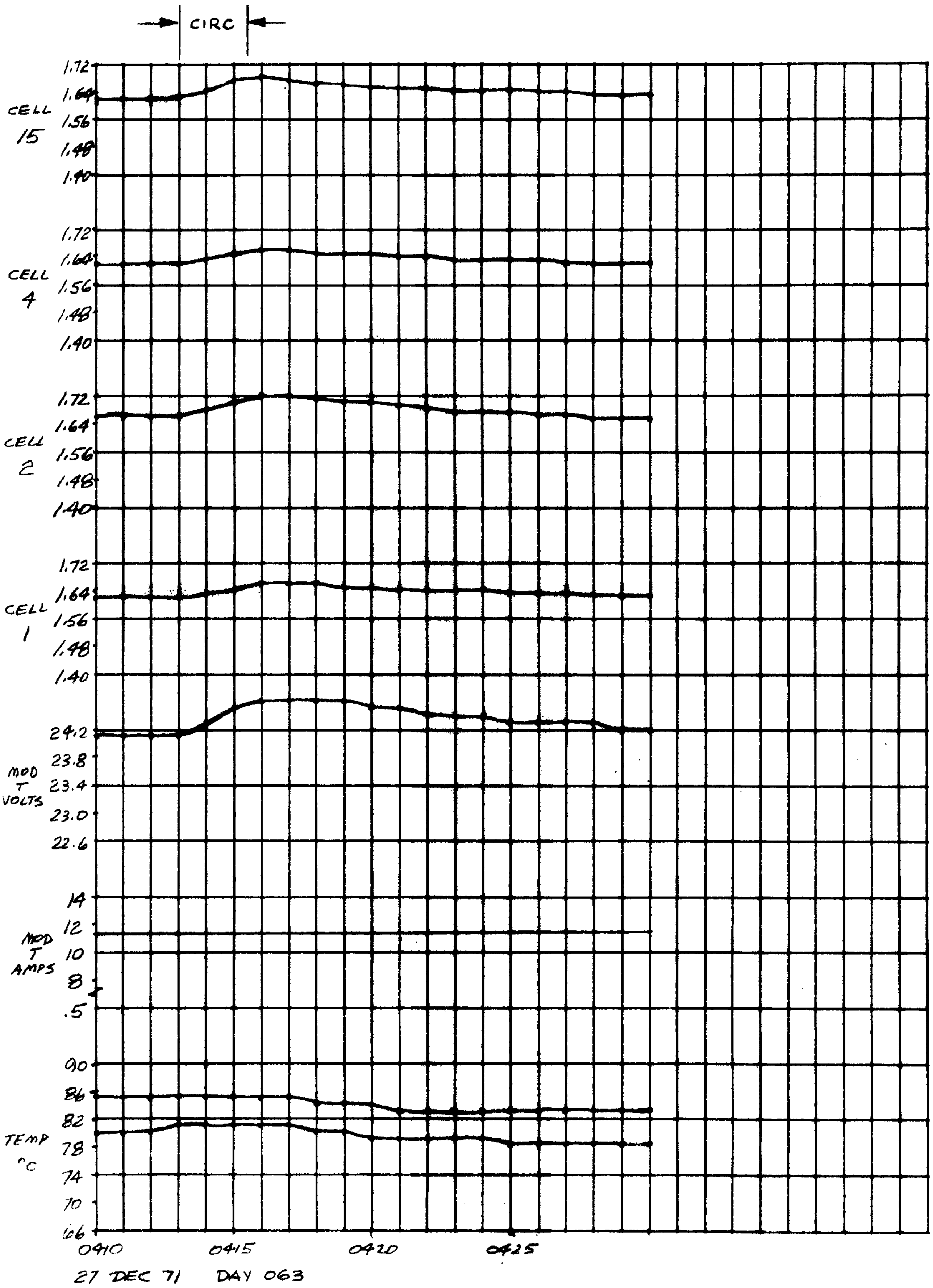


FIGURE 5-102 CIRCULATION EFFECT (POSITION 3- MODULE 3)

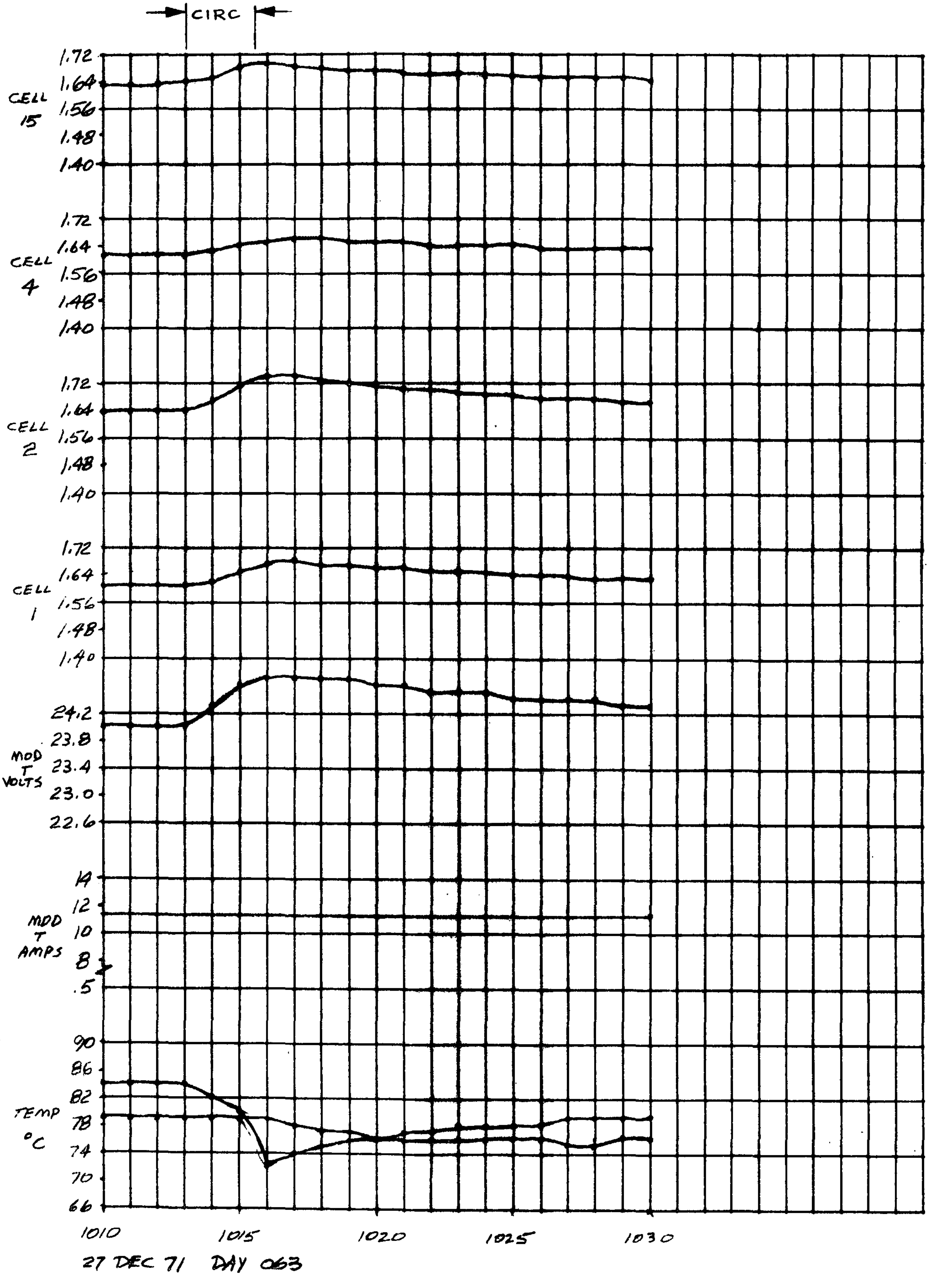


FIGURE 5-103 CIRCULATION EFFECT (POSITION 3 - MODULE 3)

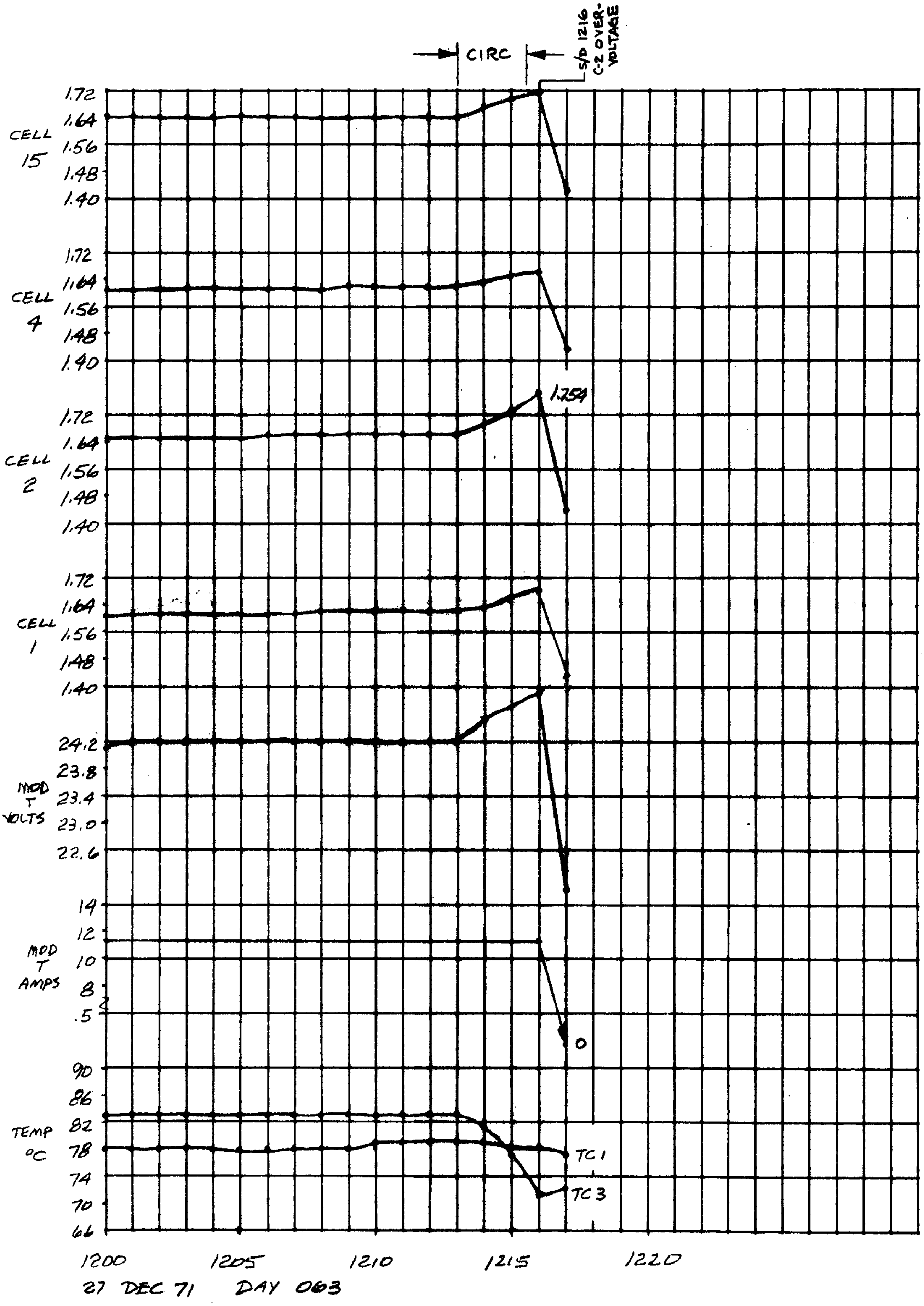
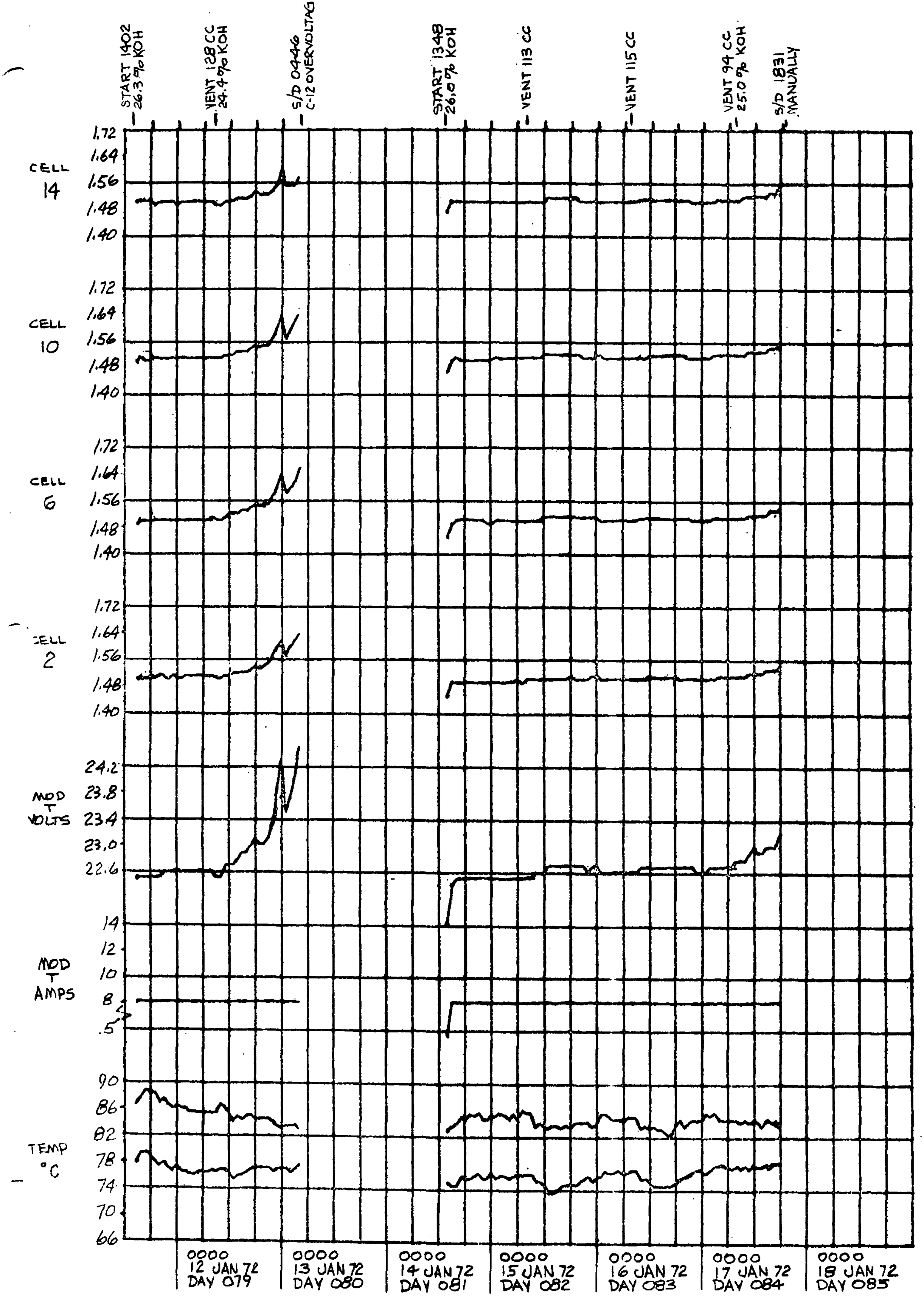


FIGURE 5-104 PERFORMANCE HISTORY (POSITION 3 - MODULE 3)



Cavity	Flush Cart Concentration Initial	 Final
H_2O	30.7%	32.8%
H_2	33.3%	33.4%
O_2	32.8%	33.3%

It is evident that the water and O_2 cavities had a significant quantity of excess KOH. The module was inspected and found to be ready for reuse after establishing proper electrolyte concentration.

The module was restarted at 1348 on 14 January and operated until 1831 on 17 January when it was manually shutdown due to excessive module voltage for the current level and an anticipated failure during the night. Cell 15 was also high in cell voltage, greater than 1.63 volts. Immediately after shutdown the module was removed from the system and all cavities drained and the samples analyzed. The results were as follows:

H_2O cavity	152 cc liquid	33.4% KOH

H_2 and O_2 cavities had zero liquid

The loop concentration was 24.1% at the time of shutdown. It should also be pointed out that the module had received a 2 1/2 minute circulation just prior to shutdown. All cavities of module 3 were placed on the flush cart. This caused the flush cart concentration to increase from 30.5% KOH to 31.4% KOH. Both the drained liquid samples and the flush cart operation indicated an excess of KOH in the water cavity of the module. A visual inspection indicated very small deposits of KOH on the exterior surfaces of the module, none of which should adversely affect module performance. As a result the module was cleaned, reflushed for proper concentration and readied for reuse.

On 20 January at 0947 the module was restarted and it continued to operate until the 115 volt AC circuit failure at 1429 on 22 January. Module performance until shutdown was reasonably stable (see Figure 5-105). System conditions were 10 minutes circulation every 6 hours with system concentration initially at 23% KOH. Module matrix concentration was 30.2%. Whether or not these conditions contributed to performance is questionable due to the untimely and early shutdown that occurred. On 24 January when module 3 was removed from the system all cavities were drained and the samples analyzed. The results are as follows:

H_2O Cavity	137 cc liquid	29.1% KOH
H_2 Cavity	6 cc liquid	33.0% KOH
O_2 Cavity	4 cc liquid	28.6% KOH

All cavities of module 3 were flushed overnight with the result that the flush cart concentration changed from 29.4% KOH to 30.5% KOH. It was after this failure that the check valve, at the electrolyte discharge of the module, was checked for back leakage of KOH. Leakage had occurred. Module 3 was carefully inspected and found ready for reuse.

As a result of the foregoing it was decided to operate the electrolyte circulating pump continuously and thereby eliminate the effect of KOH leaking back through the check valve. The concentration in the system and matrices were set at 30.2% and the module restarted at 1530 on 26 January. On 31 January the system and module temperatures were increased slightly. This increase stopped the gradual increase of module voltage and brought the maximum and minimum module temperatures closer together. Cell voltages also showed some improvement (see Figure 5-106). The module continued to operate until 1520 on 5 February, a period of 10 days. The shutdown was caused by TC1 going out of tolerance. The malfunction of the electrolyte circulation pump caused the thermocouple to indicate an increased temperature. Otherwise the module was operating very uniformly with no indications of problems. A similar high temperature condition occurred at about noon on 4 February due to zero electrolyte flow. The pump stopped for only a short period of time and hence the temperature did not reach the shutdown level.

FIGURE 5-105 PERFORMANCE HISTORY (POSITION 3- MODULE 3)

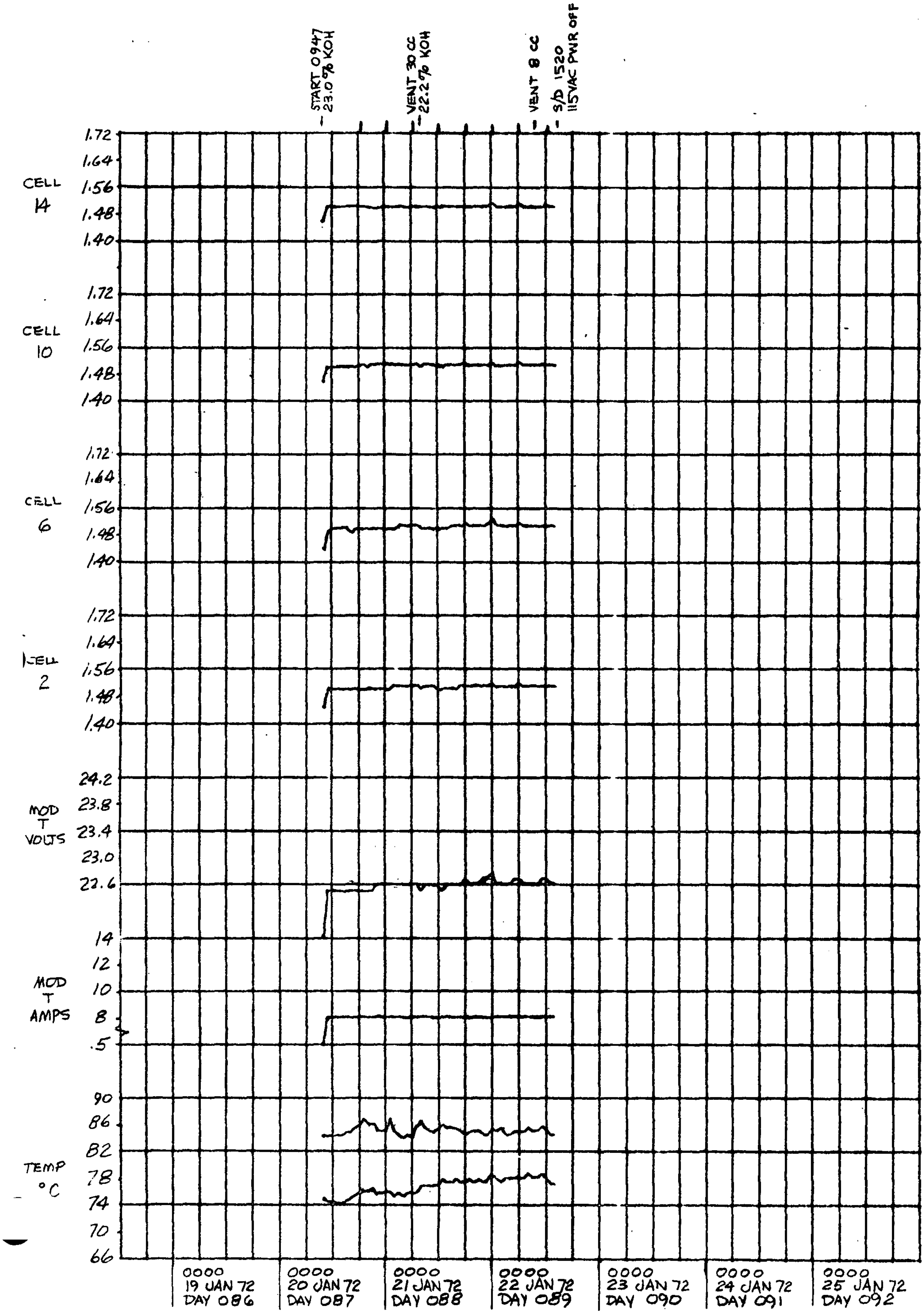


FIGURE 5-106 PERFORMANCE HISTORY (POSITION 3 - MODULE 3)
(CONTINUOUS ELECTROLYTE CIRCULATION)

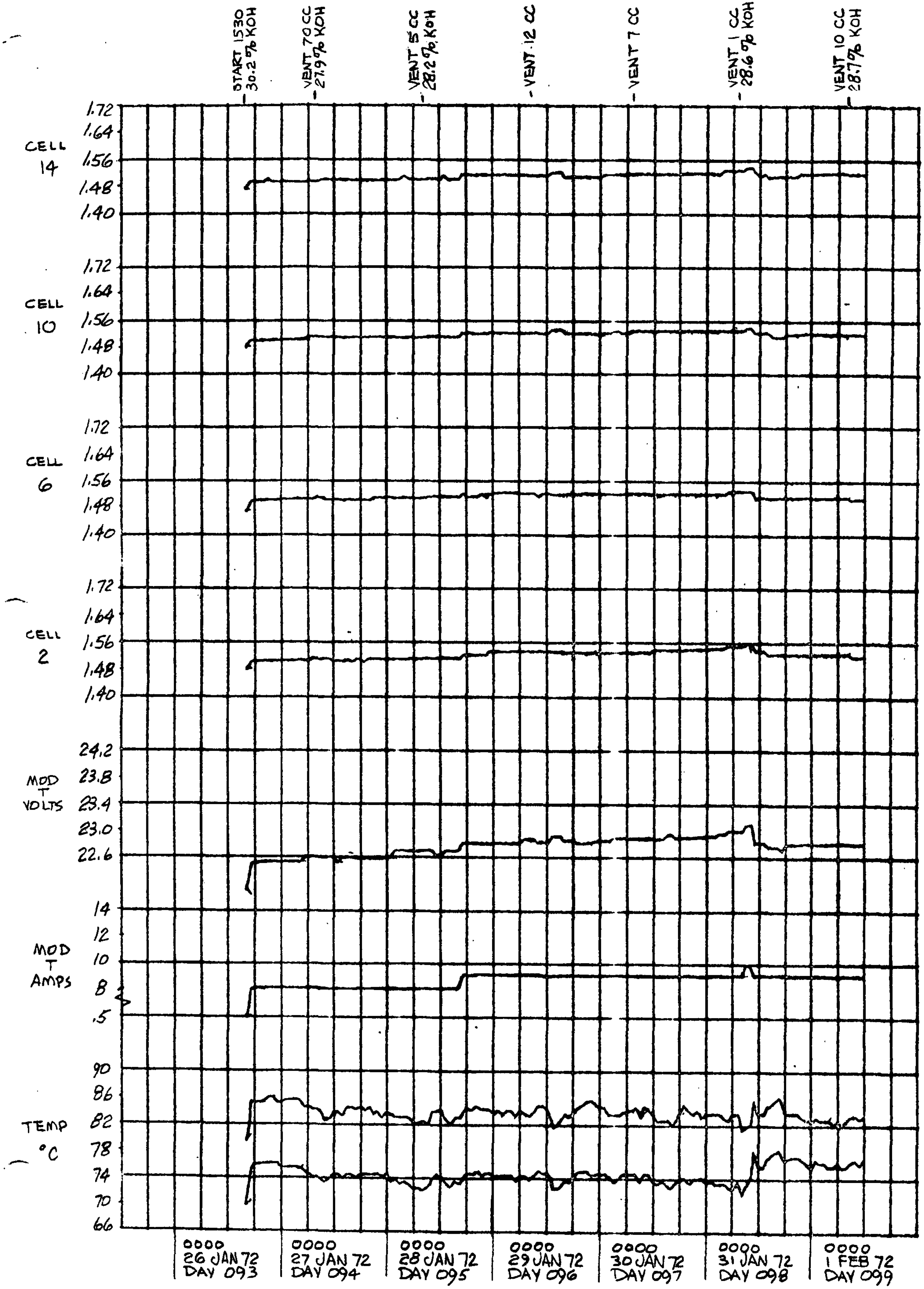


Figure 5-107 shows the performance during this period. The module was removed from the system but was not drained until 2 days later, consequently the liquid drained did not give meaningful information. Inspection of module 3 showed a slight amount of KOH at cell 1 thermocouple, between cells 1 and 2 on module top at left bolt, between cells 12 and 13 top at left bolt, at two bolts on electrode side at back, between turnaround plate and steel plate, and between cell 15 and turnaround plate. The module was placed on the flush cart and after 90 minutes no change from 30.5% KOH was found in the flush cart concentration.

The concentration in the module was increased to 35.0% and the module restarted at 1218 on 9 February and operated at 8, 10 and 11.3 amps until 0323 on 12 February when cell 9 went out of tolerance. Figure 5-108 and 5-109 show the performance during this period. The module was removed from the system and inspected. There was much evidence of external leakage. Large accumulations of KOH were found on cells 5, 6, 8 and 9 electrodes. A leak existed at TC1. KOH deposits were found on the rear end plate at compression bolt locations. Small amounts of KOH were observed on all lower heater tabs. Definite bridging of cell 9 by KOH deposits (bridge from cell 8 to cell 10) was noted. Instrumentation wires from cell 9 hydrogen electrode were found to be disconnected. All other instrumentation wires appeared to be fully connected. Some KOH was observed on cells 13, 14 and 15 electrodes. A small amount of KOH was on the front end plate, this appeared to be from the stud holes. All torques in the studs were 7.34 to 8.45 N.m (65 to 75 inch pounds).

The module was disassembled, all o-rings were found to be flattened and deformed with a permanent set. Cell 1 had a hole through the H_2O side of the cell. KOH was in contact with TC1 and cell 1 heater. The plastic was burned at the leak site. Cells 1, 2, 3, 10, 11, 12 were removed due to leaks, corrosion or other questionable appearance. Six cells were taken from Module 1 and installed in module 3. The module was pressure checked and found to be leak tight.

FIGURE 5-107 PERFORMANCE HISTORY (POSITION 3 - MODULE 3)

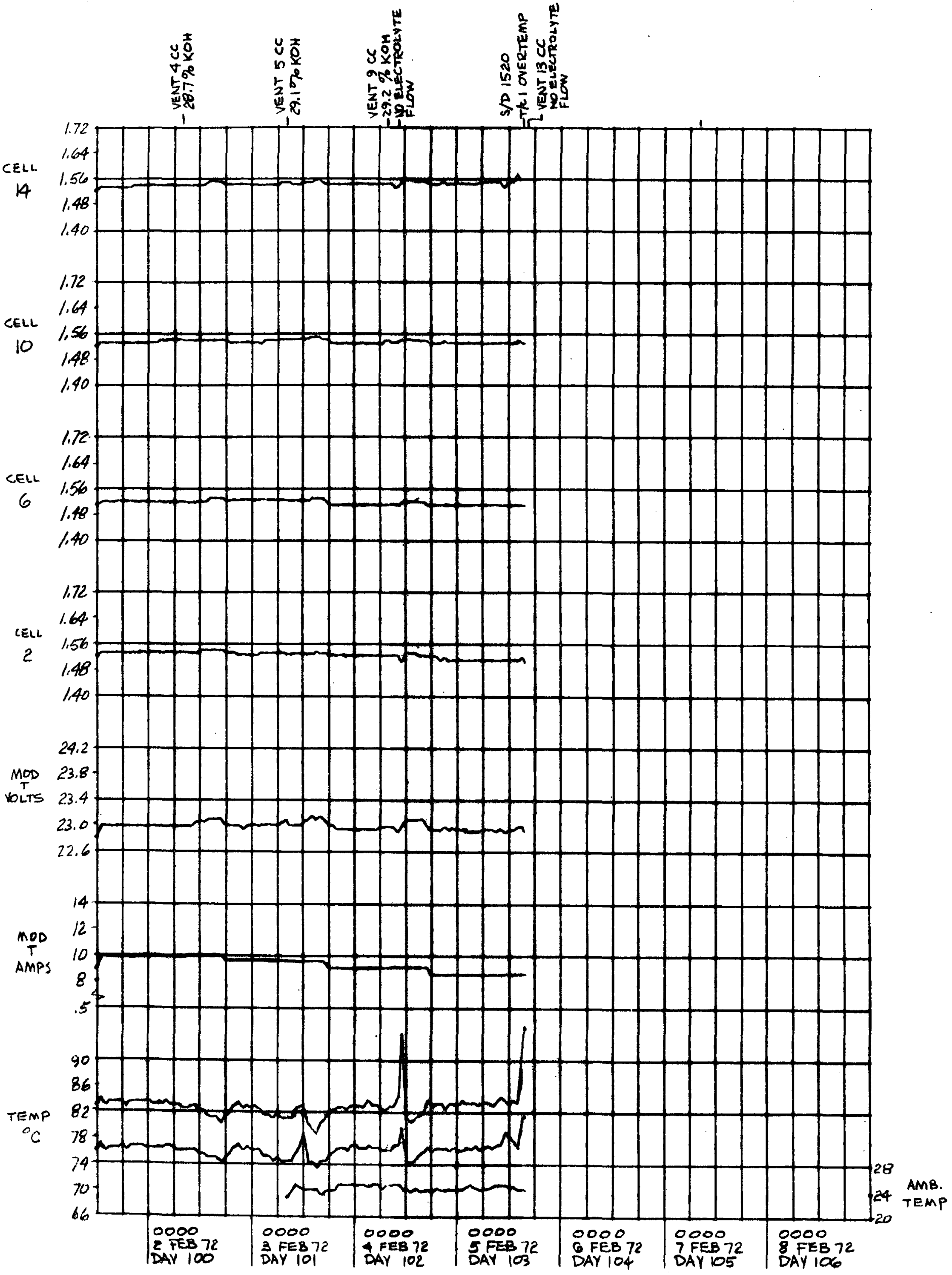


FIGURE 5-108 PERFORMANCE HISTORY (POSITION 3- MODULE 3)

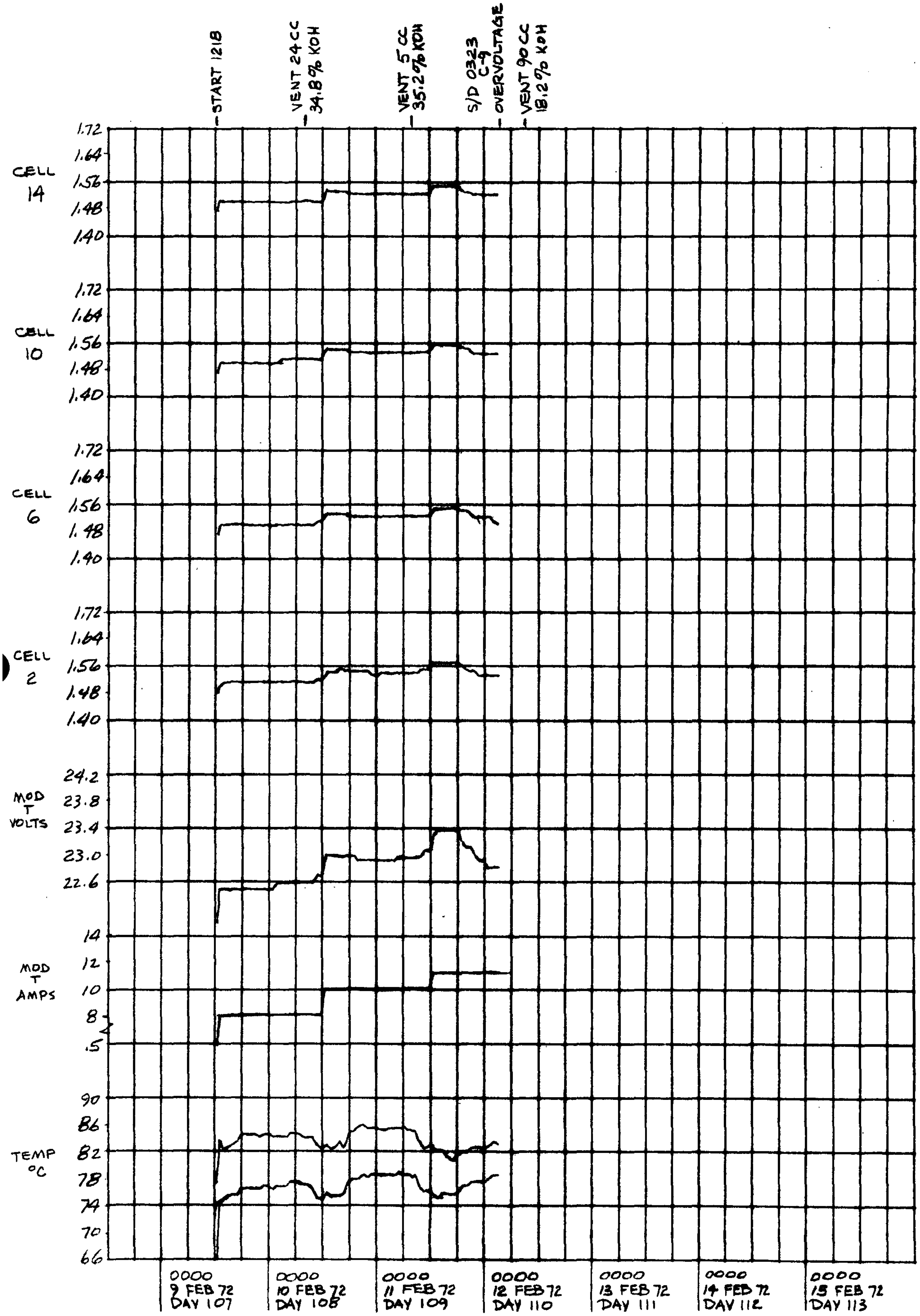
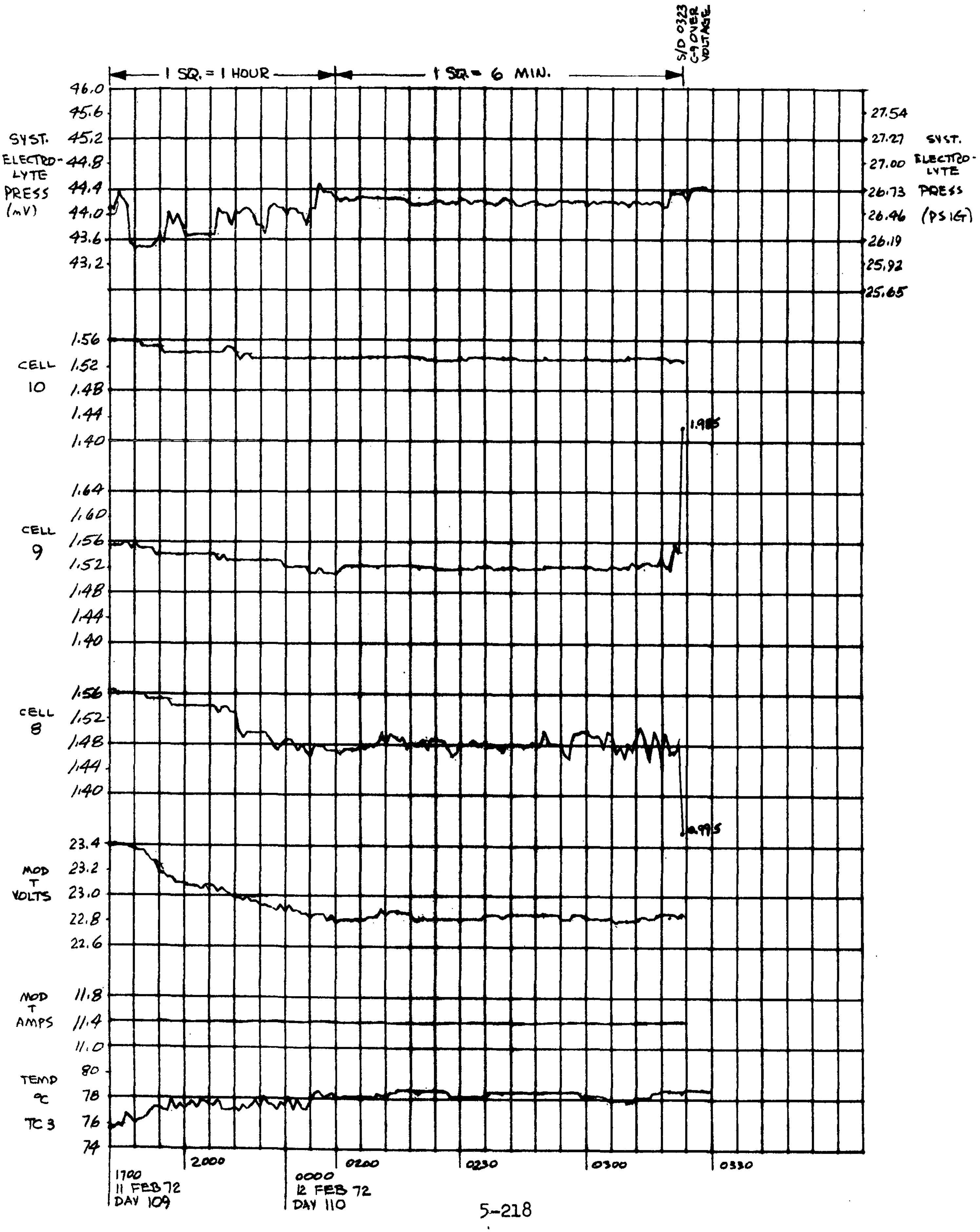


FIGURE 5-109 DETAILED PERFORMANCE BEFORE FAILURE (POSITION 3 - MODULE 3)



The module was flushed with 30.0 to 30.5% KOH and made ready for restart. On 21 February at 1143 the module was restarted and operated until 1600 at which time the module was shutdown by the computer due to a false control signal. The set point on the temperature control meter was stuck and had continually requested heating in the module. The problem was corrected and the module restarted at 1639. Figures 5-110 and 5-111 show the performance from 21 through 29 February. This module did not show any abnormalities during the two times that KOH was added to the electrolyte loop. Cell voltages were flat and uniform without adverse trends.

The module continued to operate until 0015 on 4 March (a period of 11.5 days). Shutdown was caused by overvoltage in cell 15. The module was allowed to equalize for about 10 hours and was restarted at 0954 on 4 March. The module operated until 1215 on 16 March (a period of 12 days). Performance of the module during these two operating periods is shown on Figures 5-112, 5-113 and part of 5-114. After the shutdown on 16 March the module was removed from the system and all cavities drained. The H_2O cavity had 134 cc's with a concentration of 26.9% KOH. Loop concentration at this time was 25.2% KOH, implying some KOH concentrating in the water matrices. Less than 0.5 cc of liquid was collected from each of the H_2 and O_2 cavities. A visual inspection was conducted that indicated only a few small patches of KOH which did not warrant module disassembly. The module was flushed to reestablish proper matrix concentrations and plumbing was modified to allow water feed at the top of the module.

The module was restarted at 1635 on 16 March and operated until shutdown manually at 1207 on 22 March. The manual shutdown was to return the plumbing to normal conditions and allow operation with water feed at the bottom and 14 cells instead of 15 cells. Operation with top water feed is shown on Figure 5-114. Inspection of the figure reveals the same characteristics as demonstrated on module 2. During the 2.5-hour shutdown on 22 March a visual inspection showed the module to be in good condition with only a few small patches of KOH on the external surfaces. The module was restarted on 1437 on

FIGURE 5-110 PERFORMANCE HISTORY (POSITION 3 - MODULE 3)

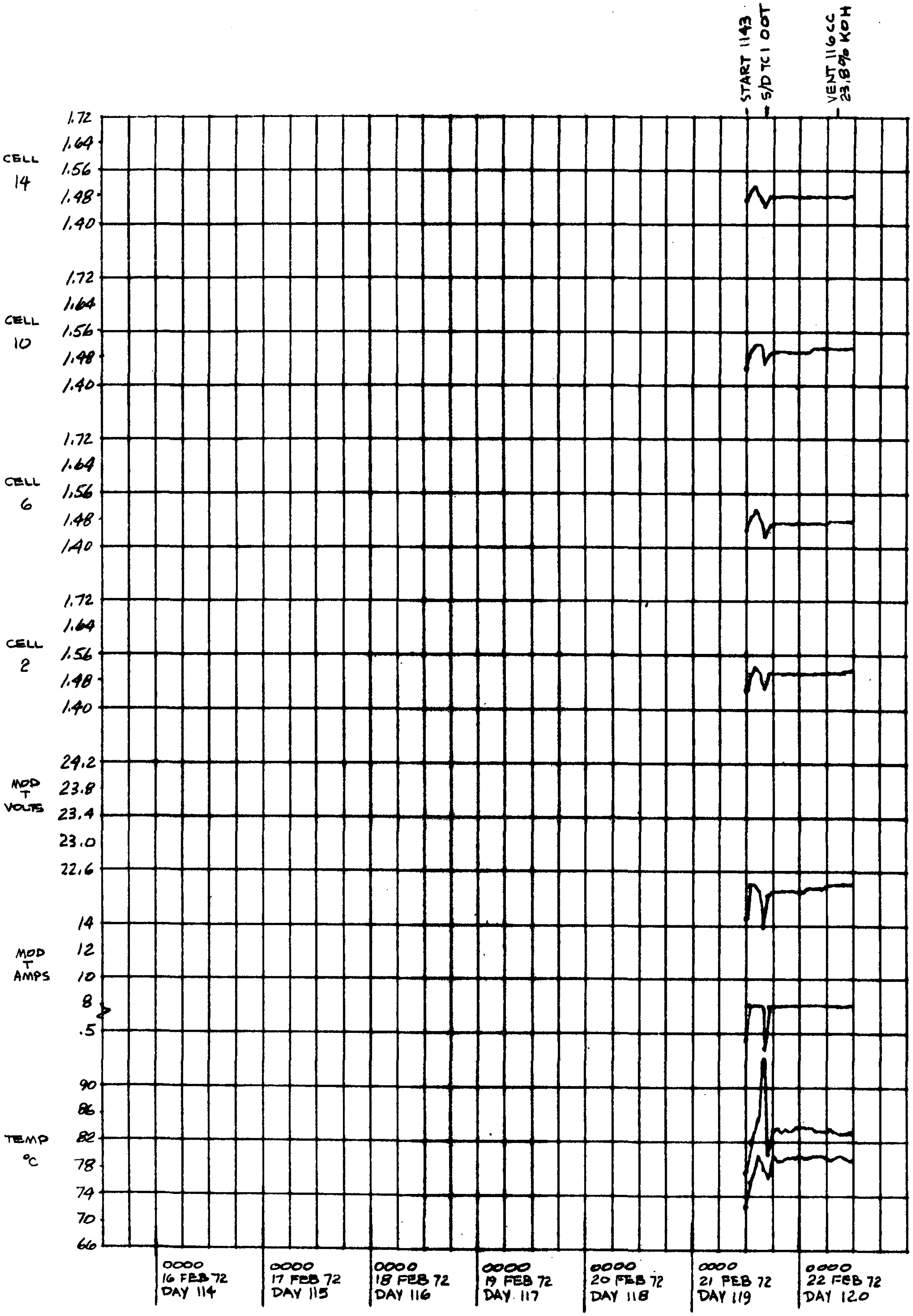


FIGURE 5-111 PERFORMANCE HISTORY (POSITION 3 - MODULE 3)

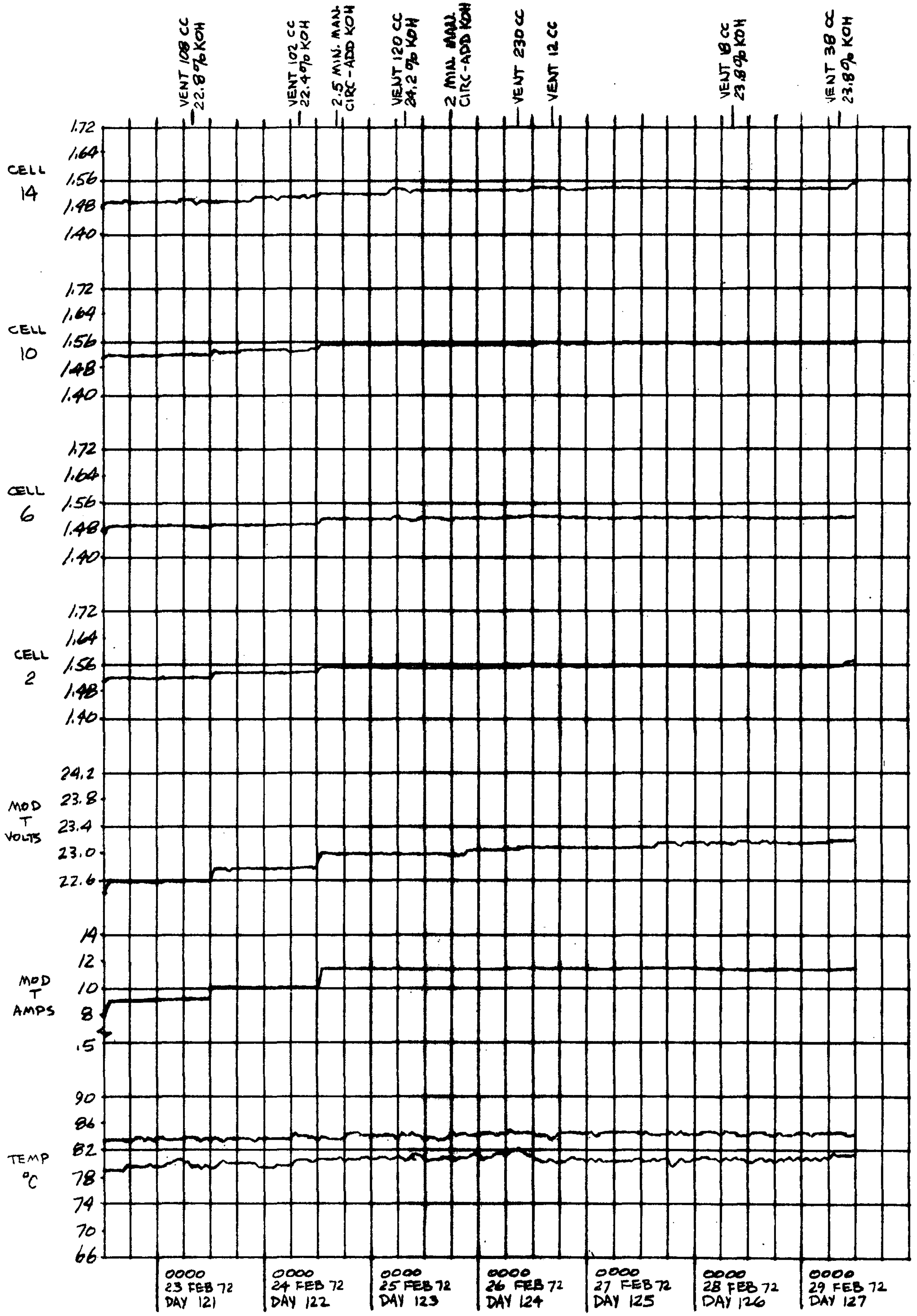


FIGURE 5-112 PERFORMANCE HISTORY (POSITION 3 - MODULE 3)

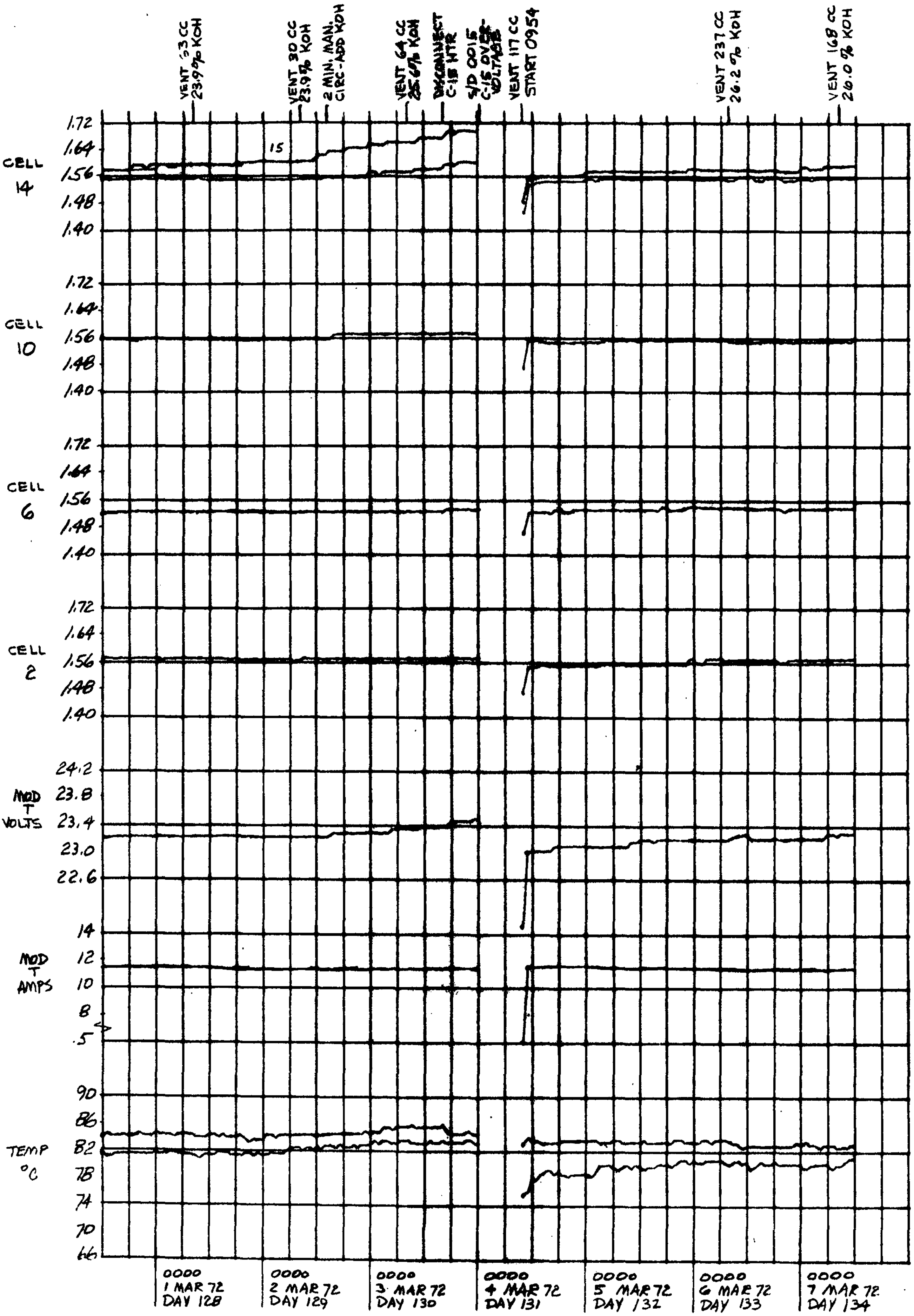


FIGURE 5-113 PERFORMANCE HISTORY (POSITION 3 - MODULE 3)

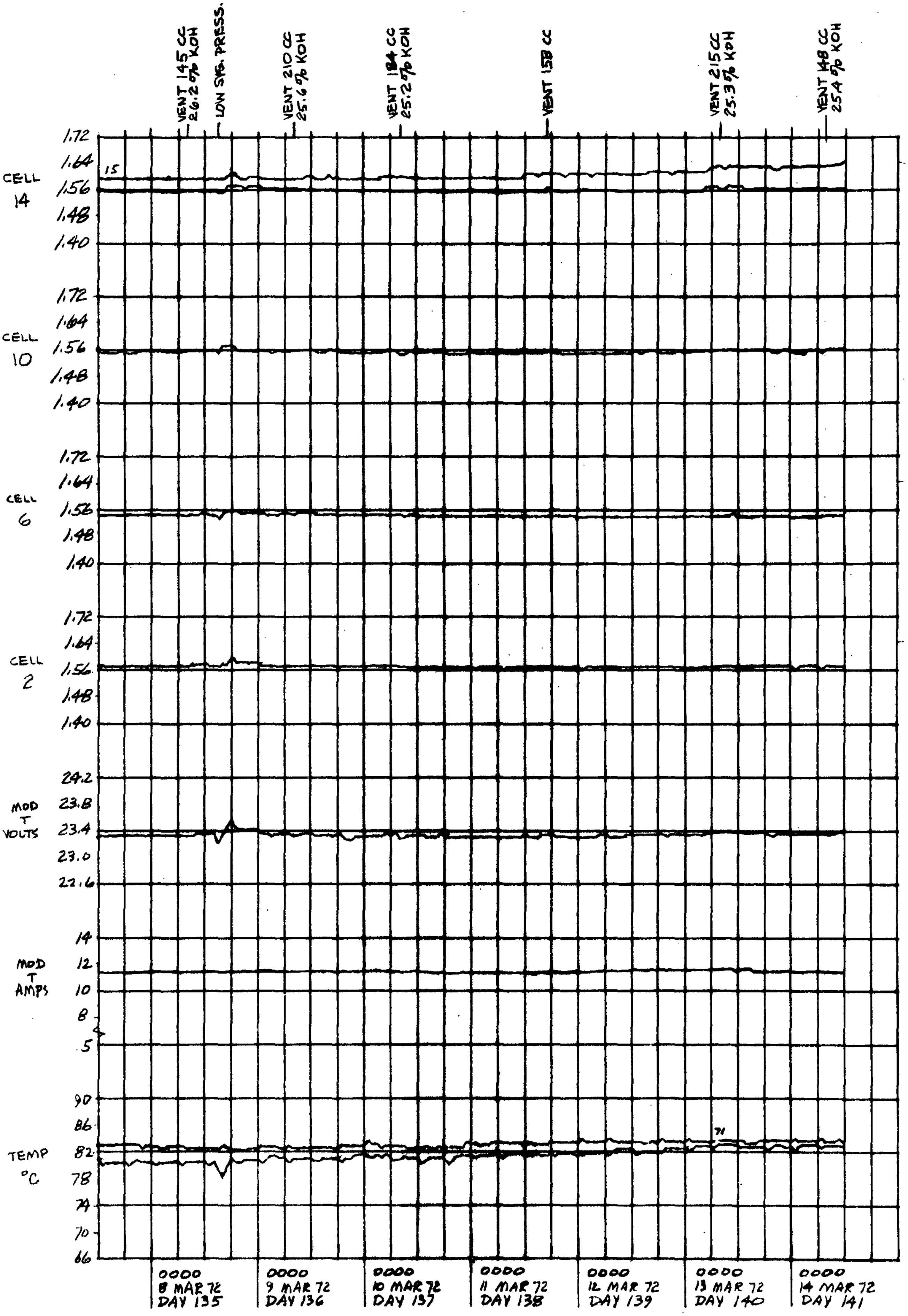
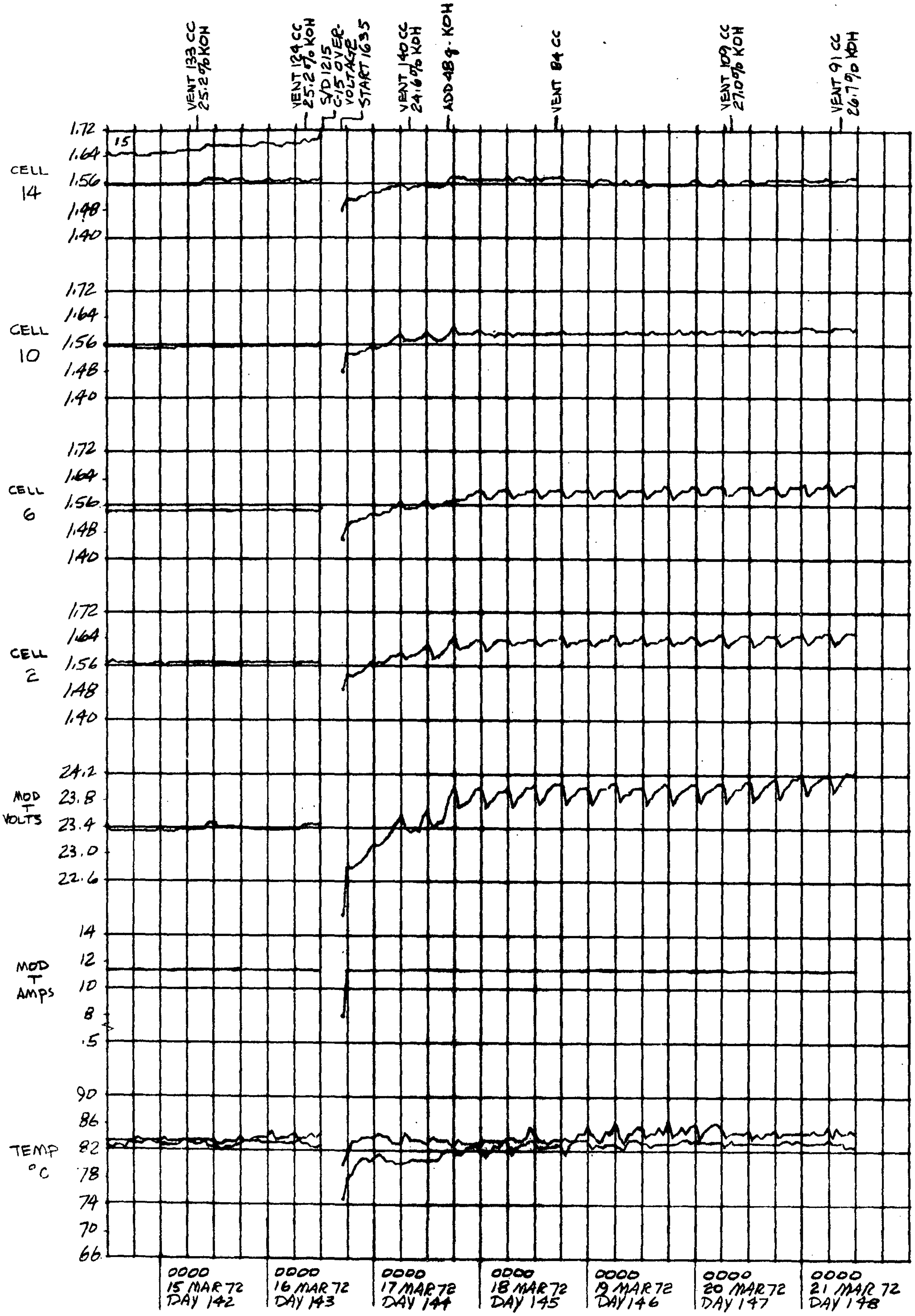


FIGURE 5-114 PERFORMANCE HISTORY (POSITION 3- MODULE 3)



22 March and continued to operate until 1616 on 30 March (a period of 8 days). Figure 5-115 shows the performance of the module from 22 March. Shutdown was caused by cell 14 overvoltage. Only 14 cells were in use at this time. Nothing was done to the module, it remained in the system at pressure and was subjected to normal electrolyte circulations. At 0805 on 31 March the module was restarted and continued to operate until 1531 on 6 April when the entire system was shutdown due to a failure of the data acquistion system. Figure 5-116 and part of Figure 5-117 show the performance of the module during these periods. At the time of shutdown on 6 April all cells were performing nicely except cell 14 which was experiencing the usual voltage rise due to electrolyte washout.

The next morning, the module was removed from the system and all cavities drained. The H_2O cavity had 125 cc's, the other cavities did not have any liquid. The visual inspection revealed: a small amount of KOH on top of the module between cells 1 through 5, a small amount of KOH on upper heater tab of cell 14 and between turnaround plate and cell 15 on electrode side, some KOH on lower corner of module (electrode side) between cell 1 and the spacer plate, cell 4 through 6, cell 7 and 8, and cell 15 and the turnaround plate, KOH on bottom of module at cell 1, cells 3 and 4, cells 7 and 8 and cell 15. The module was considered in good condition and did not warrant disassembly. Cell 15 was reconnected electrically and the module flushed. The module was restarted at 1201 on 7 April and continued to operate until shutdown manually at 1423 on 12 April. The manual shutdown was performed because it was apparent that cell 15 would go out of tolerance at any time and a modification was planned for the circulation loop timers.

The module was restarted at 1647 on the same day and operated until shutdown automatically by the data acquisition system failure at 2045 on 14 April. Next morning, the module was removed from the system and flushed on the flush cart and restarted at 0957 on 15 April and continued to operate until manually shutdown at 1140 on 19 April. Figure 5-118 shows the performance of the module between 11 April and 18 April. The dashed lines on the

FIGURE 5-115 PERFORMANCE HISTORY (POSITION 3- MODULE 3)

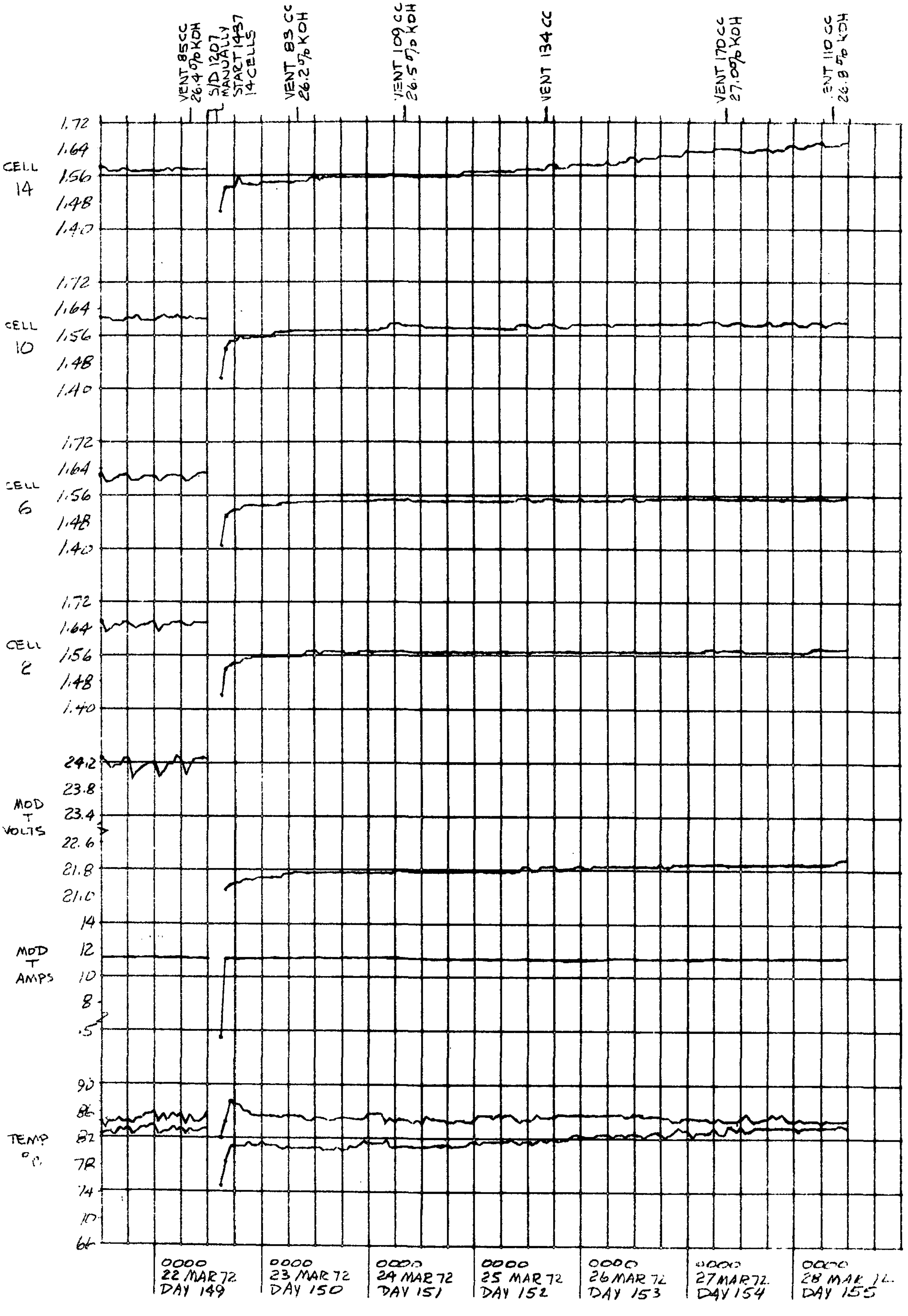


FIGURE 5-116 PERFORMANCE HISTORY (POSITION 3 - MODULE 3)

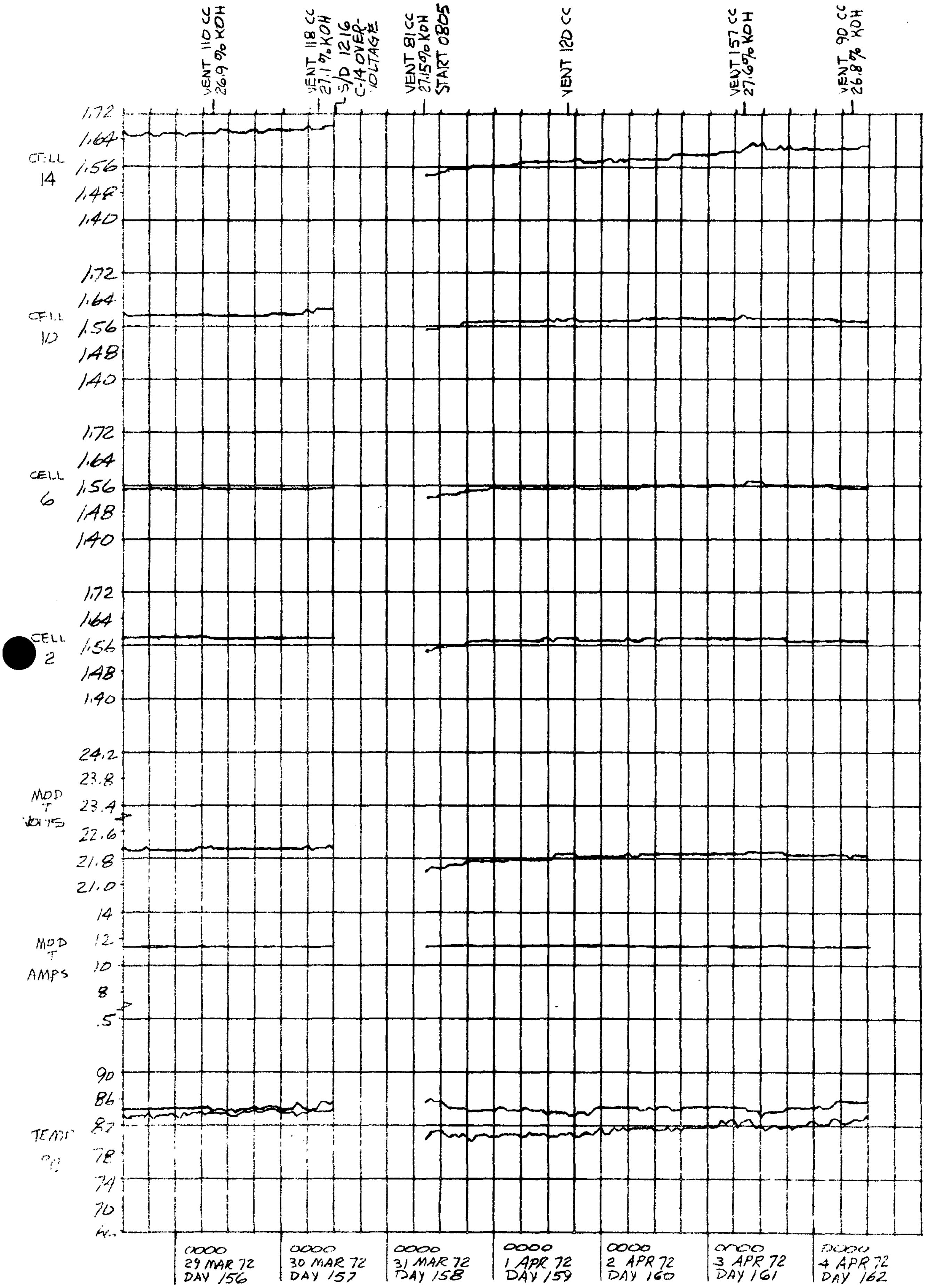


FIGURE 5-117 PERFORMANCE HISTORY (POSITION 3- MODULE 3)

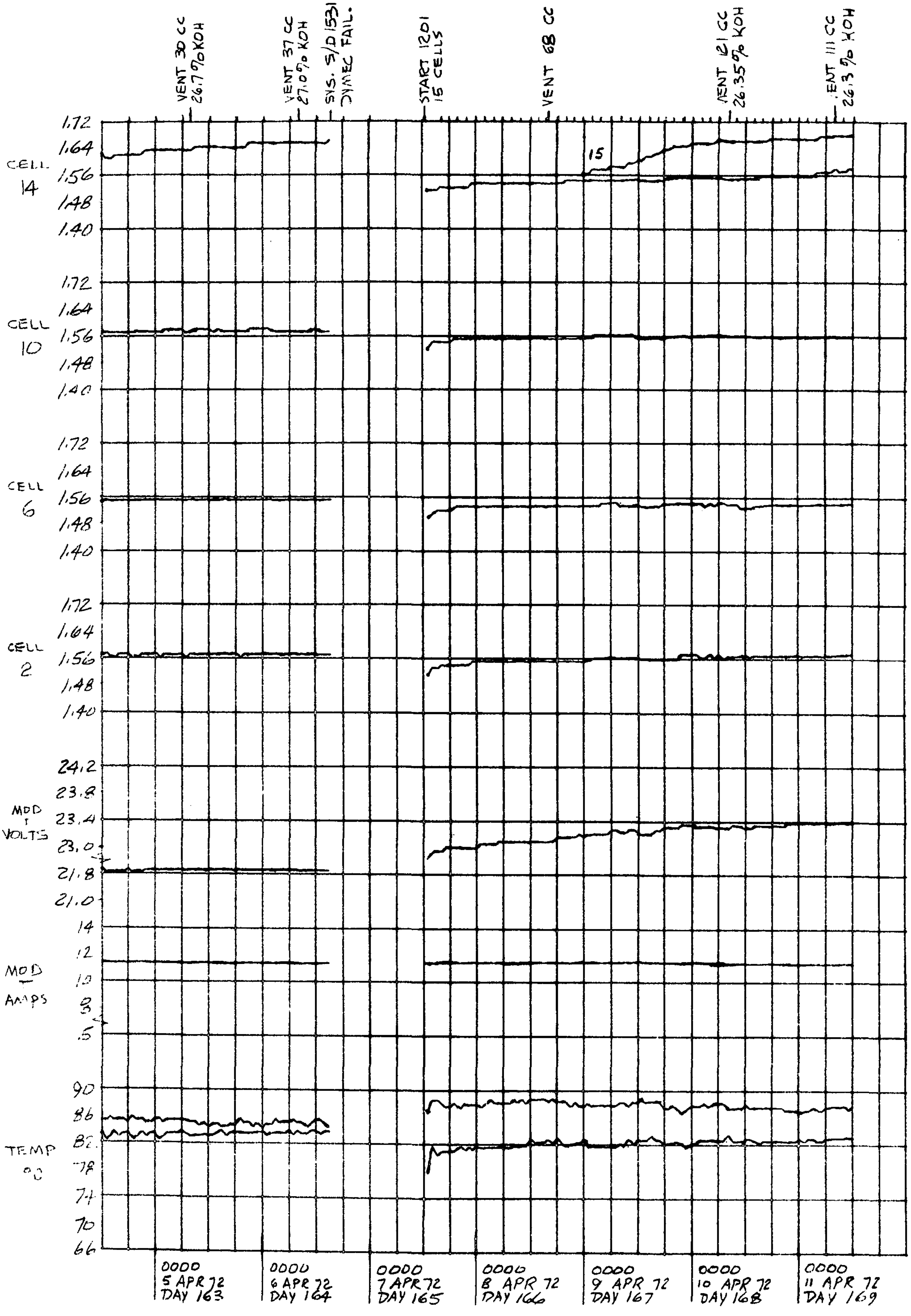
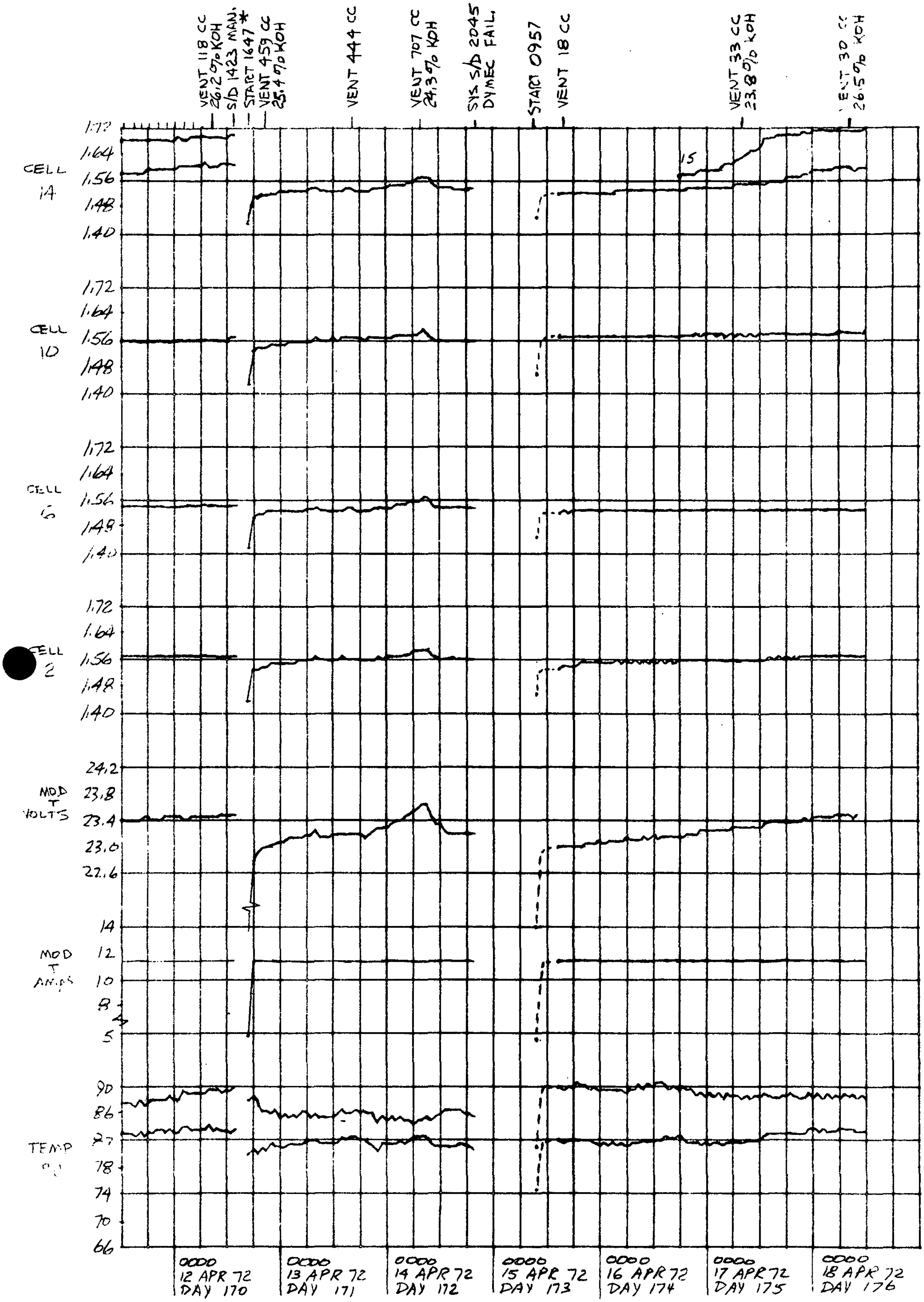


FIGURE 5-118 PERFORMANCE HISTORY (POSITION 3 - MODULE 3)



* START 30 SEC CIRC EVERY 40 MIN., FLOW THRU ALL MODS. SIMULTANEOUSLY.

figure reflect the condition of operation based on visual observation rather than on data system printout as the Dymec was undergoing repairs. The manual shutdown on 19 April was because cell 15 was almost out of tolerance and it was desired to change the electrolyte concentration and modify the circulation configuration.

After all adjustments were made the module was restarted at 1407 on 19 April and continued to operate until 0834 on 25 April when it was shutdown automatically due to overvoltage in cell 15. The module was not restarted as the test ended at 1200 on 25 April. Performance of the module during the last week is shown on Figure 5-119.

5.7.2.4 Module 4

Figures 5-120 through 5-127 show the detailed performance of this module during the period 21 October through 2 November 1971. The low temperature indicated on 21 and 22 October was caused by the operator leaving the selector switch set on thermocouple number 3 of the module. The computer tends to read 10°K (18°F) lower than actual when this occurs. The correct temperature should be approximately 348°K (167°F). This module operated from 1630 on 22 October to 2245 on 29 October (174 hours) with very uniform performance except for cells 13-15. These cells showed slowly increasing cell voltages from 26 October. Inspecting the module after failure on 29 October revealed a quantity of dried KOH located adjacent to cells 13-15. This was very similar to the KOH accumulation reported by LSI after acceptance testing the module. The module had been carefully inspected and tested for leaks prior to use but all tests were negative. After this failure all the module cavities were flushed on the flush cart for 30 minutes. Initial concentration of KOH in the flush cart was 30.4, 30 minutes later it was 26.1% and 45 minutes later still at 26.1%. This indicates a very low level of KOH in the module cavities at the time of failure. Next the module was disassembled and cells 13 through 15 inspected for damage. No structural damage was evident. KOH was seen between all cells and one tension stud had been blackened. Slight burning of plastic around the heater wire copper tab existed but there was no significant

FIGURE 5-119 PERFORMANCE HISTORY (POSITION 3 - MODULE 3)

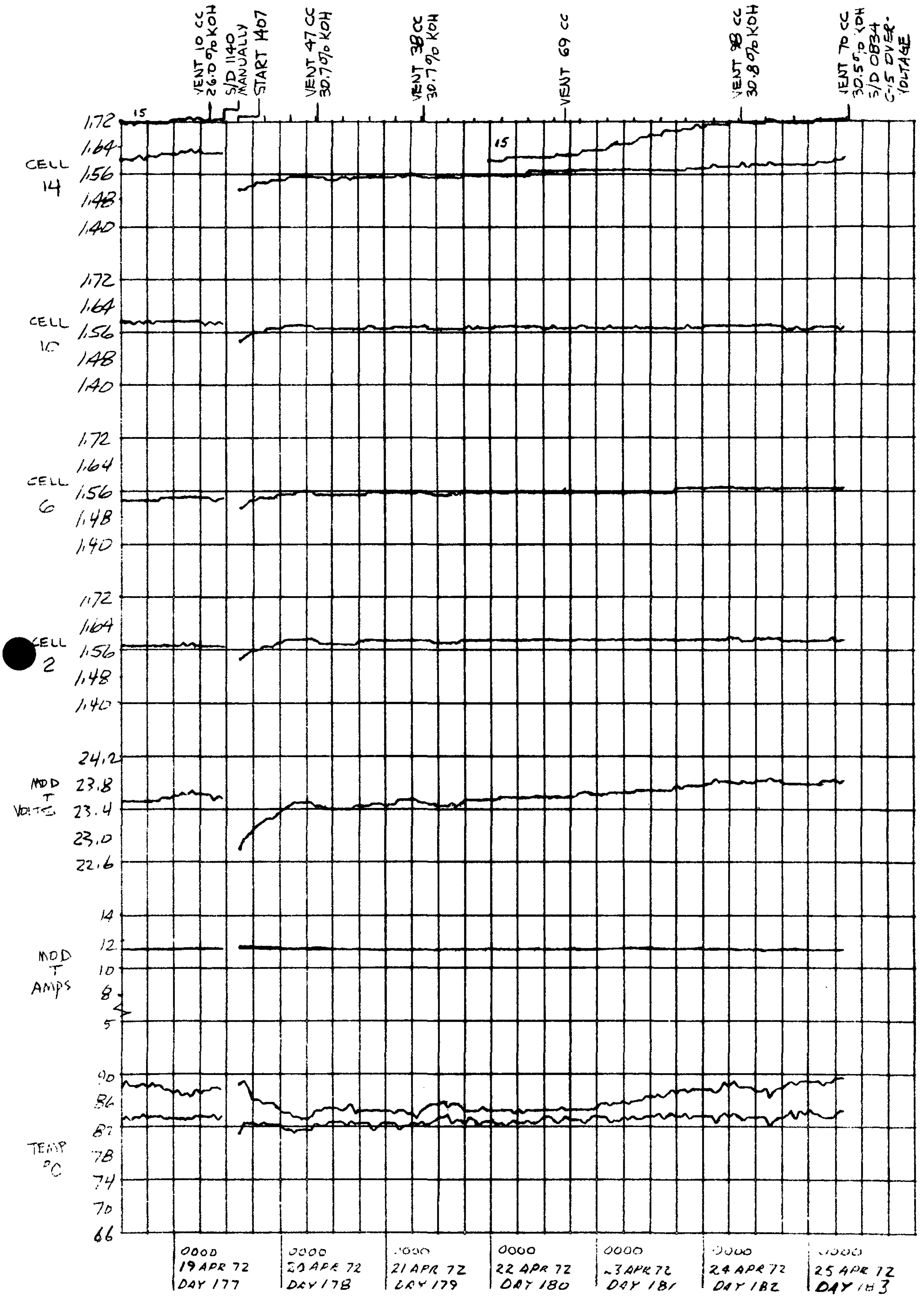


FIGURE 5-120 PERFORMANCE HISTORY (POSITION 1- MODULE 4)

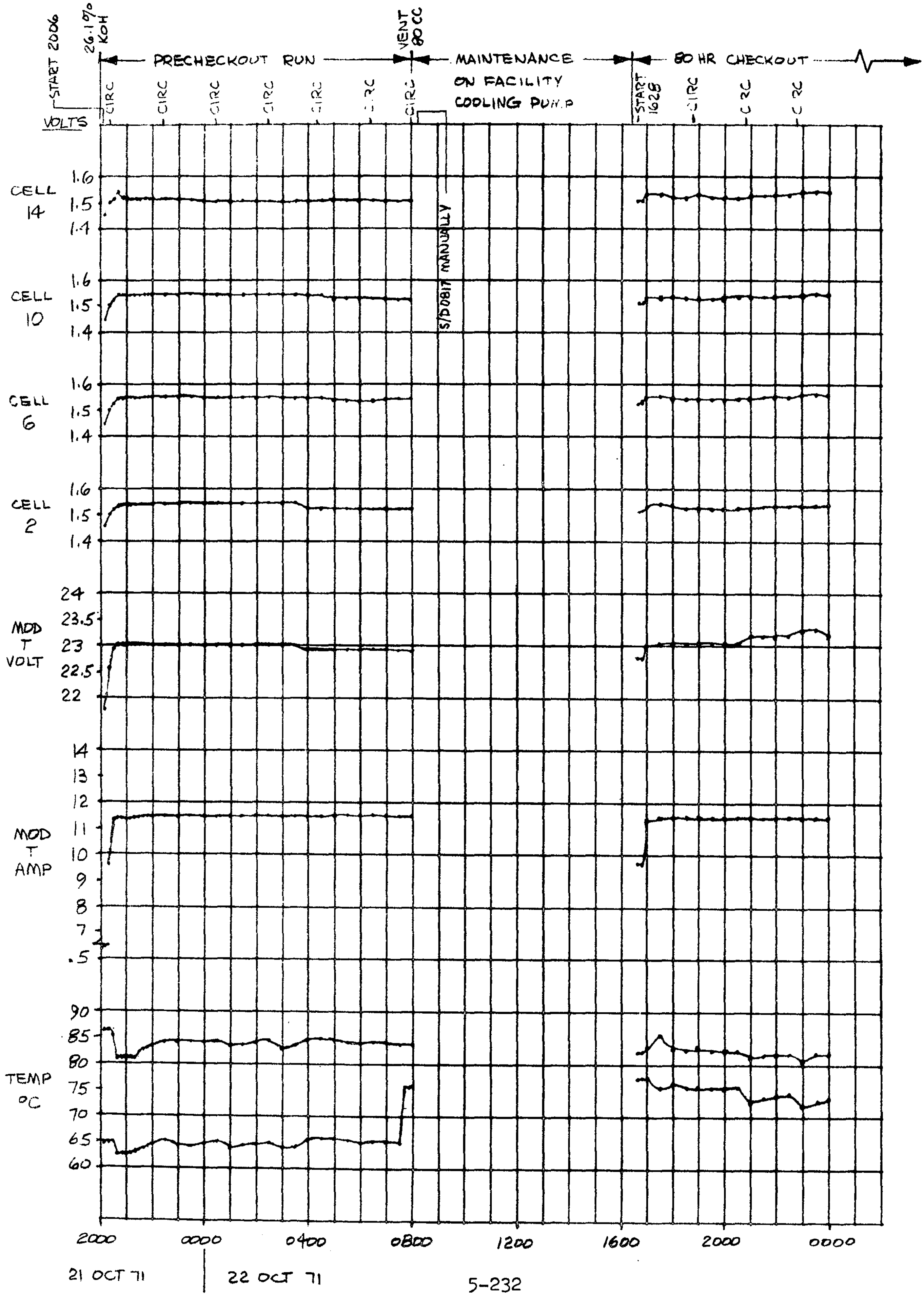


FIGURE 5-121 PERFORMANCE HISTORY (POSITION 1-MODULE 4)

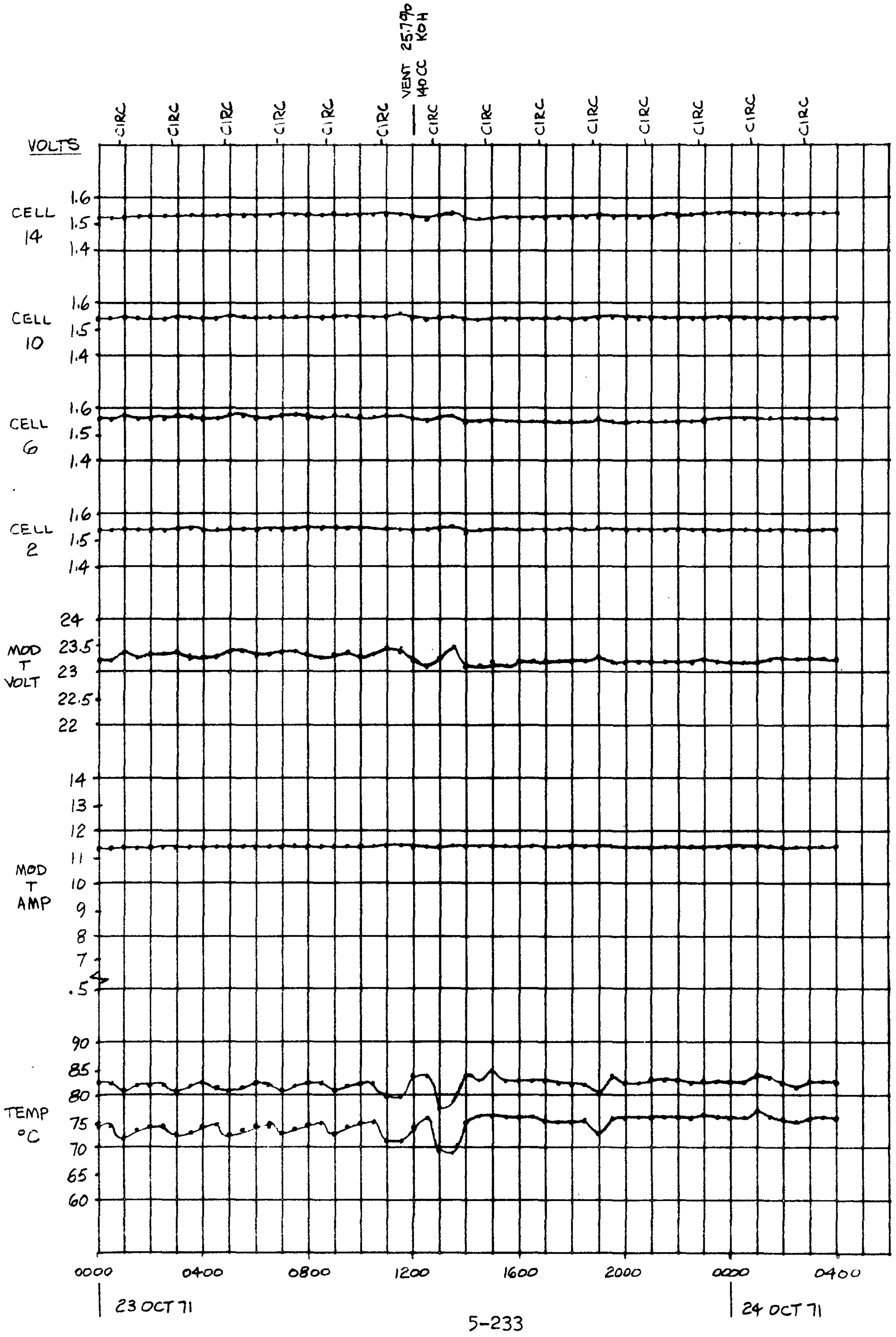


FIGURE 5-122 PERFORMANCE HISTORY (POSITION 1-MODULE 4)

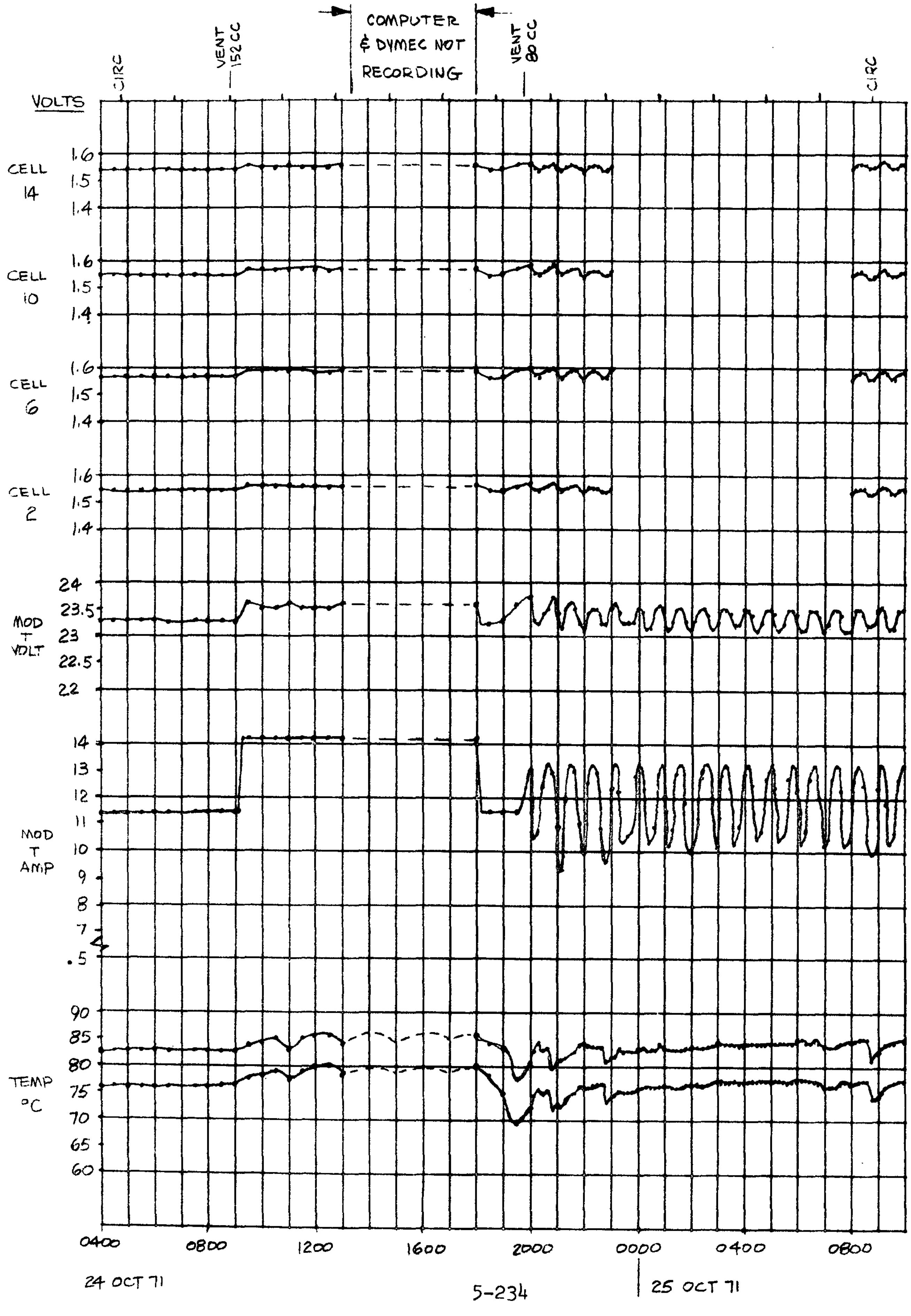


FIGURE 5-123 PERFORMANCE HISTORY (POSITION 1- MODULE 4)

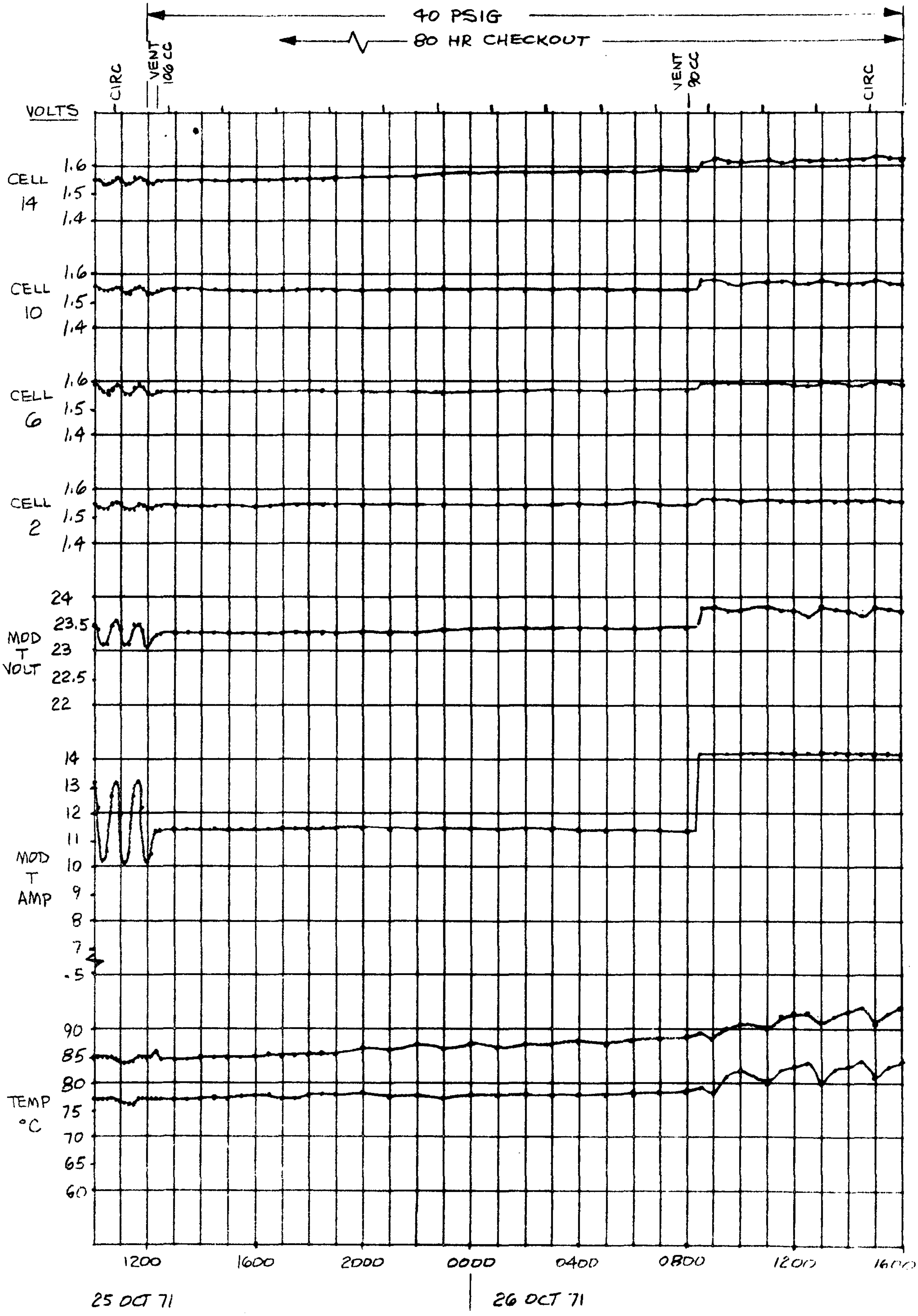


FIGURE 5-124 PERFORMANCE HISTORY (POSITION 1-MODULE 4)

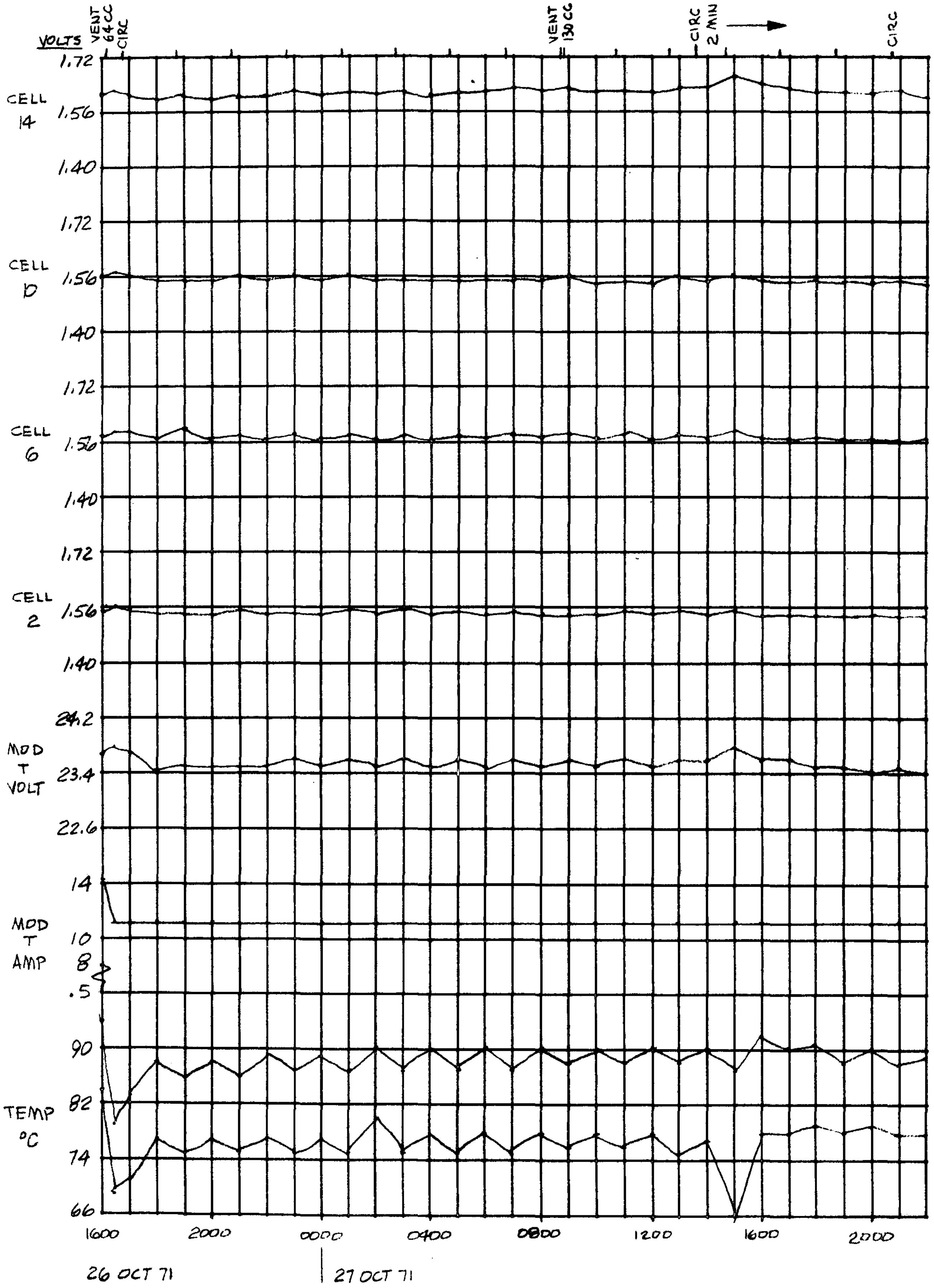


FIGURE 5-125 PERFORMANCE HISTORY (POSITION 1 - MODULE 4)

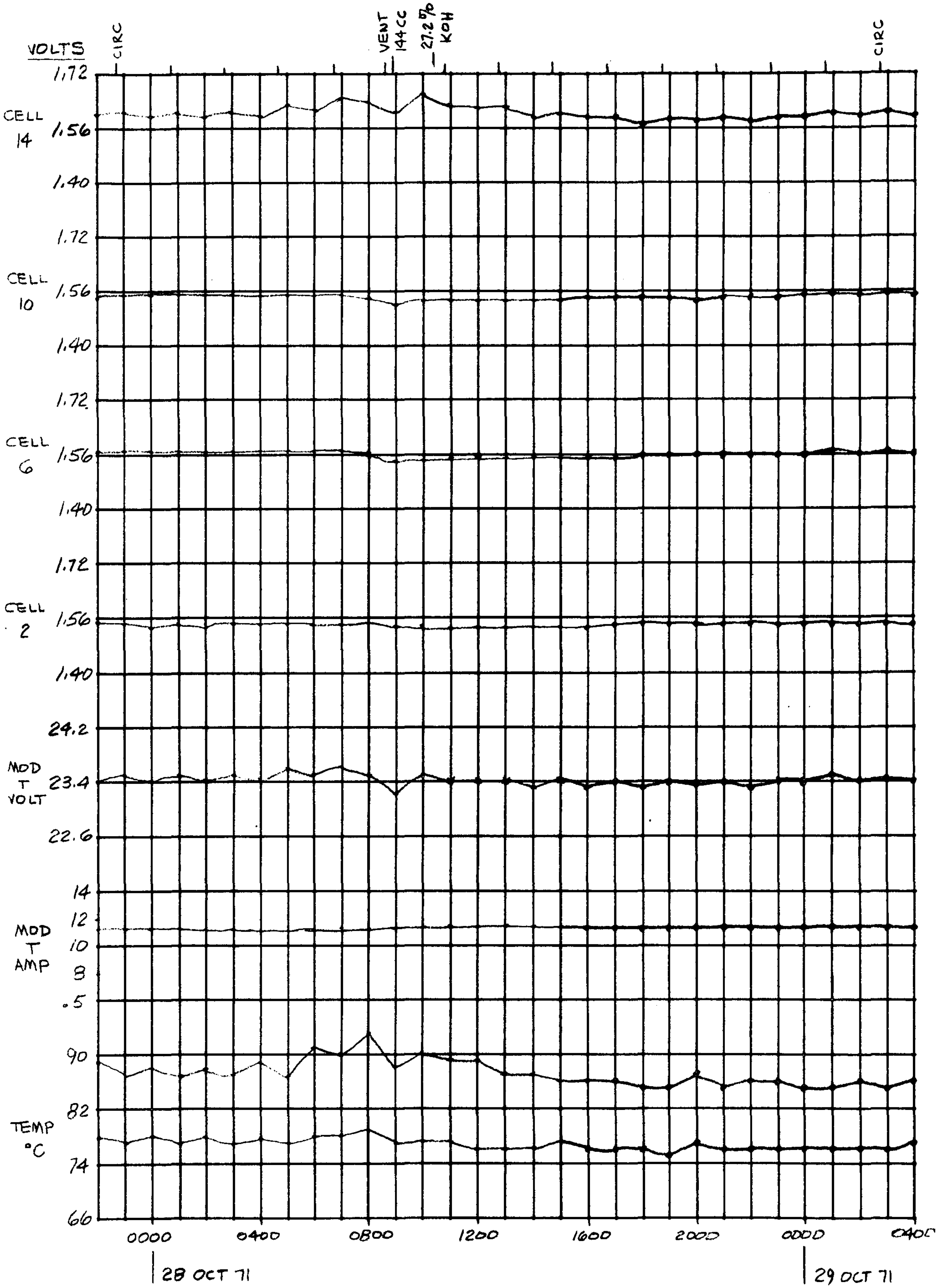


FIGURE 5-126 PERFORMANCE HISTORY (POSITION 1-MODULE 4)

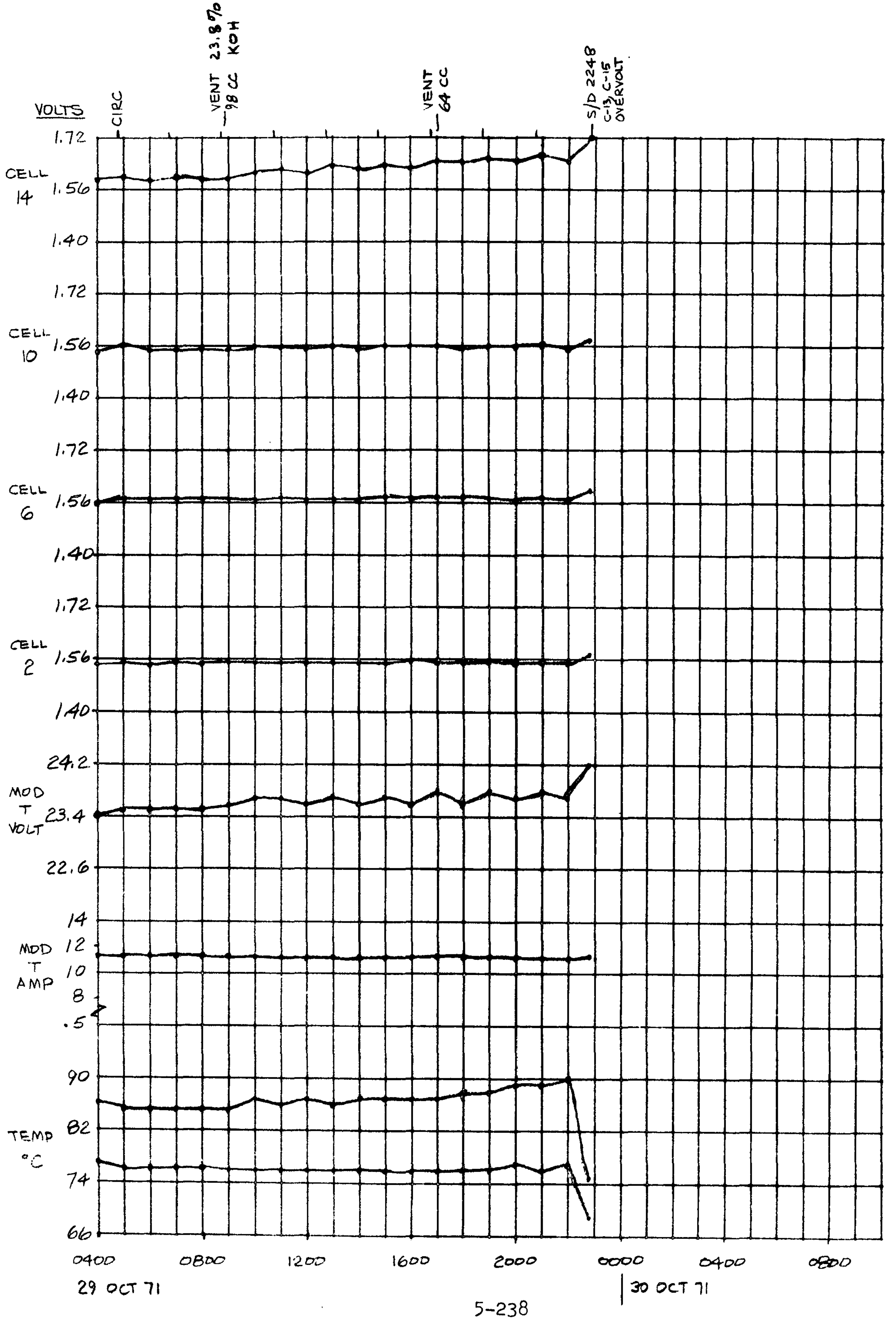
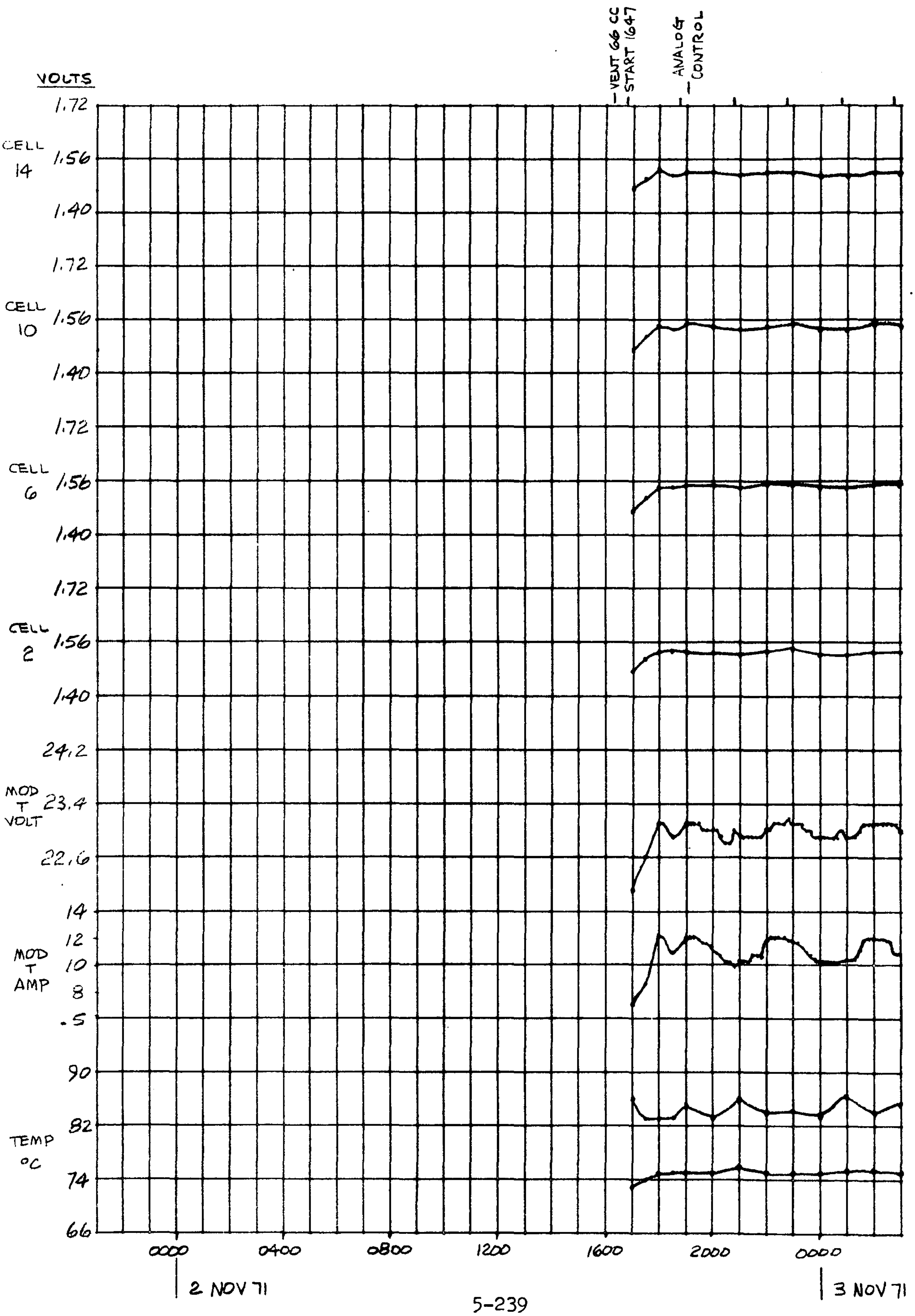


FIGURE 5-127 PERFORMANCE HISTORY (POSITION 1-MODULE 4)



damage. The cells were cleaned, the thermocouple wires were resoldered and properly insulated, new (larger crosssectional diameter) o-rings were added and the module was reassembled. After assembly the module was crossleak checked and external leak checked. There was no evidence of leaks. The module was flushed overnight and the concentration in the flush cart adjusted to 30.0% KOH. The module was back on the line at 1630 on 2 November 1971. Electrolyte concentration variations within the system seem to have little effect on the performance of this module.

Figures 5-128 through 5-135 show the performance of this module during the period 3 through 30 November. The module was started at 1700 on 2 November and operated continuously except for three momentary shutdowns due to problems associated with the data acquisition system. The module operated about 882 hours without a shutdown due to module malfunction. Figures 5-128 and 5-129 show the performance of the module during analog control. Steady state operation was initiated at 0900 on 5 November. Figures 5-128 through 5-133 show a gradual increase in module voltage until the short term (9 minutes) shutdown occurred on 9 November. This seems to have allowed the module to recover. Within 24 hours the module voltage began to climb to 23.6 where the rate of change slowed and a more gradual increase occurred. The rapid rise and high level performance between 0800 on 28 November and 0800 on 29 November occurred when only 2 modules were operating in the system. After 0800 on 29 November, module 4 was operated alone. The increased flow rate of electrolyte during circulation periods seems to have improved the performance of the module.

At approximately 2000 on 13 November thermocouple number 4 appeared to change indicated values. A review of printed data indicated that the end plate heater on the module had stopped working. This was caused by the end plate heater wire becomming disconnected. Figure 5-136 shows an expanded plot of the change in performance and a corresponding increase in cell 15 voltage due to the loss of heater power.

FIGURE 5-128 PERFORMANCE HISTORY (POSITION 1 - MODULE 4)

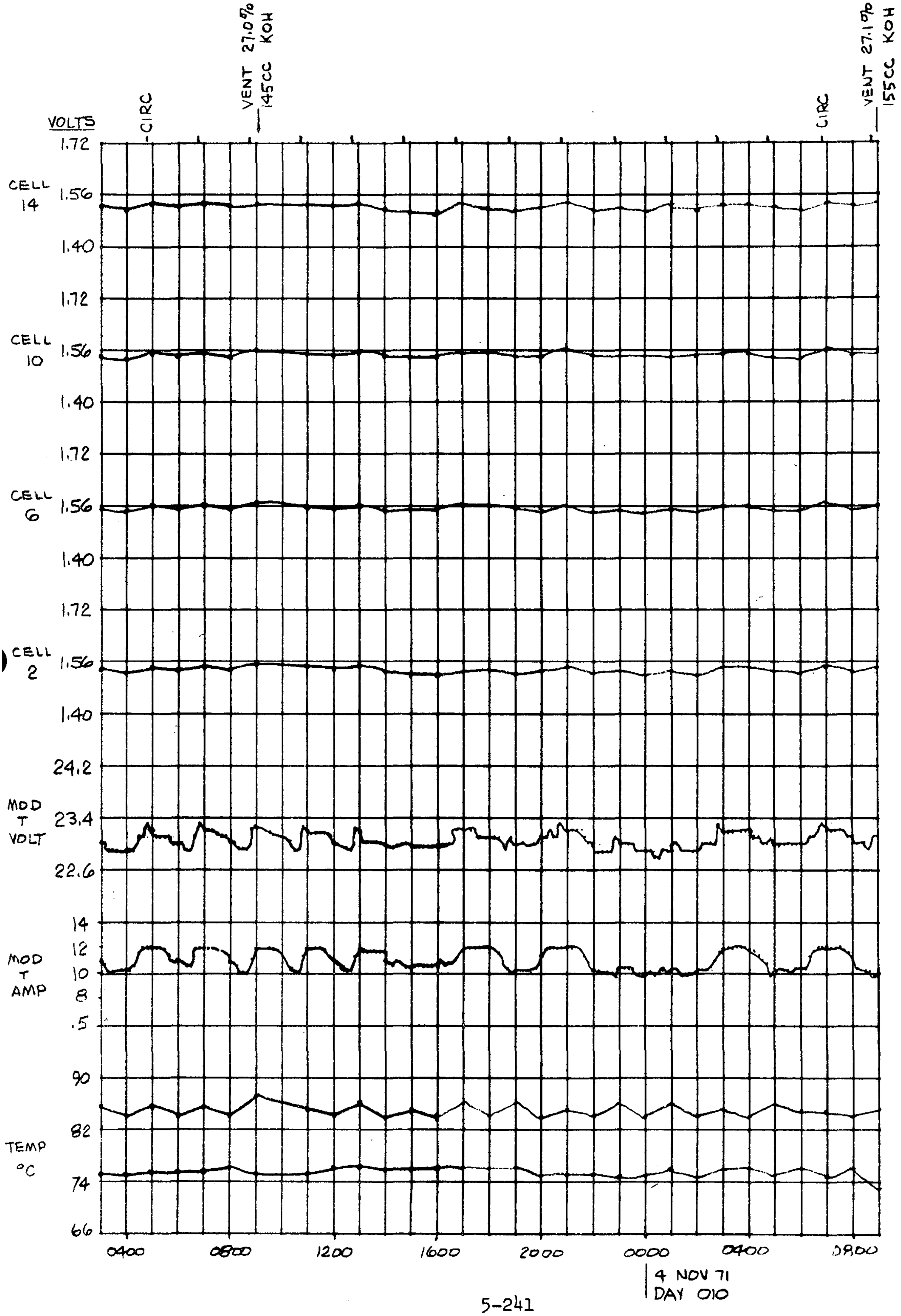


FIGURE 5-129 PERFORMANCE HISTORY (POSITION 1-MODULE 4)

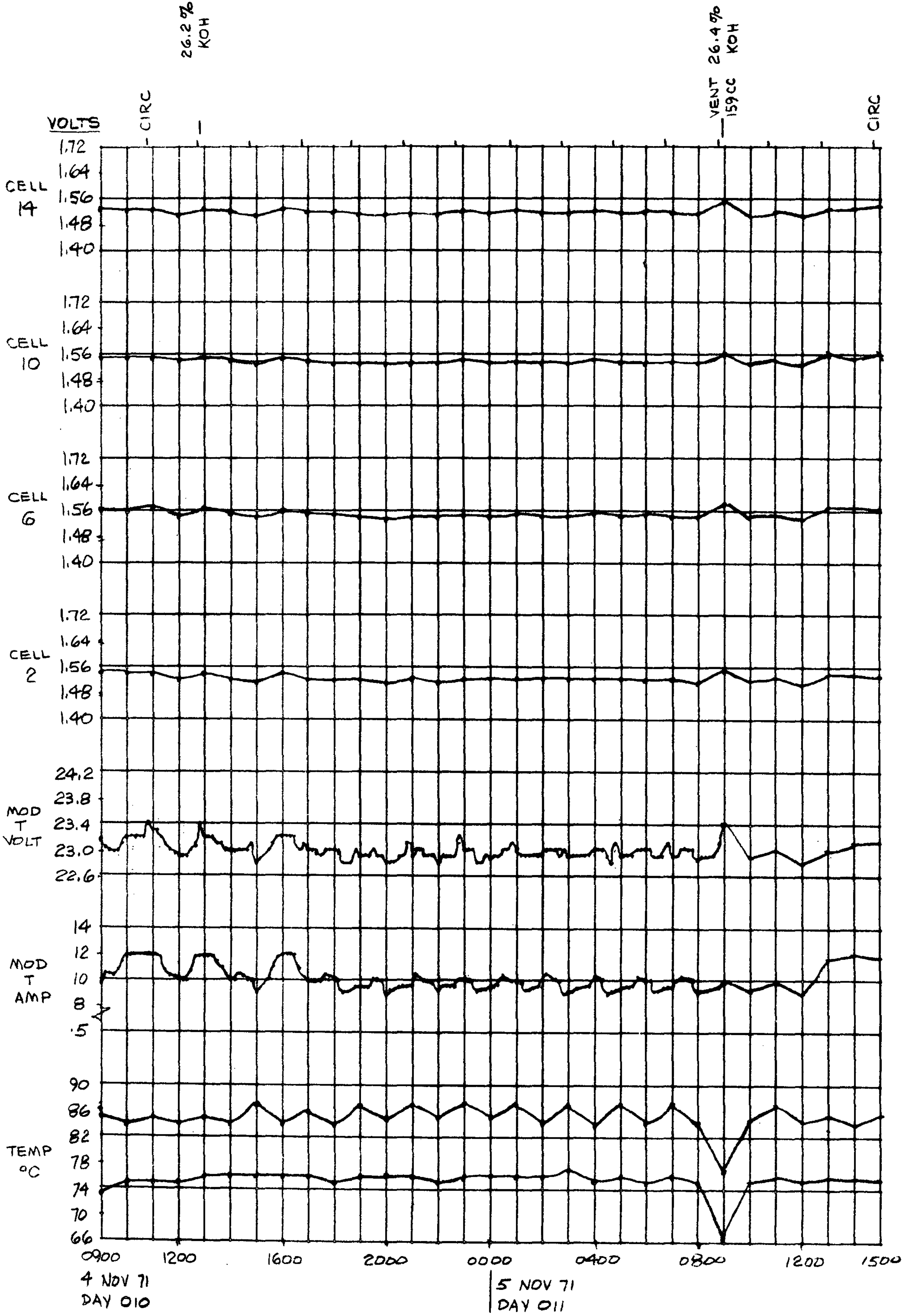


FIGURE 5-130 PERFORMANCE HISTORY (POSITION 1- MODULE 4)

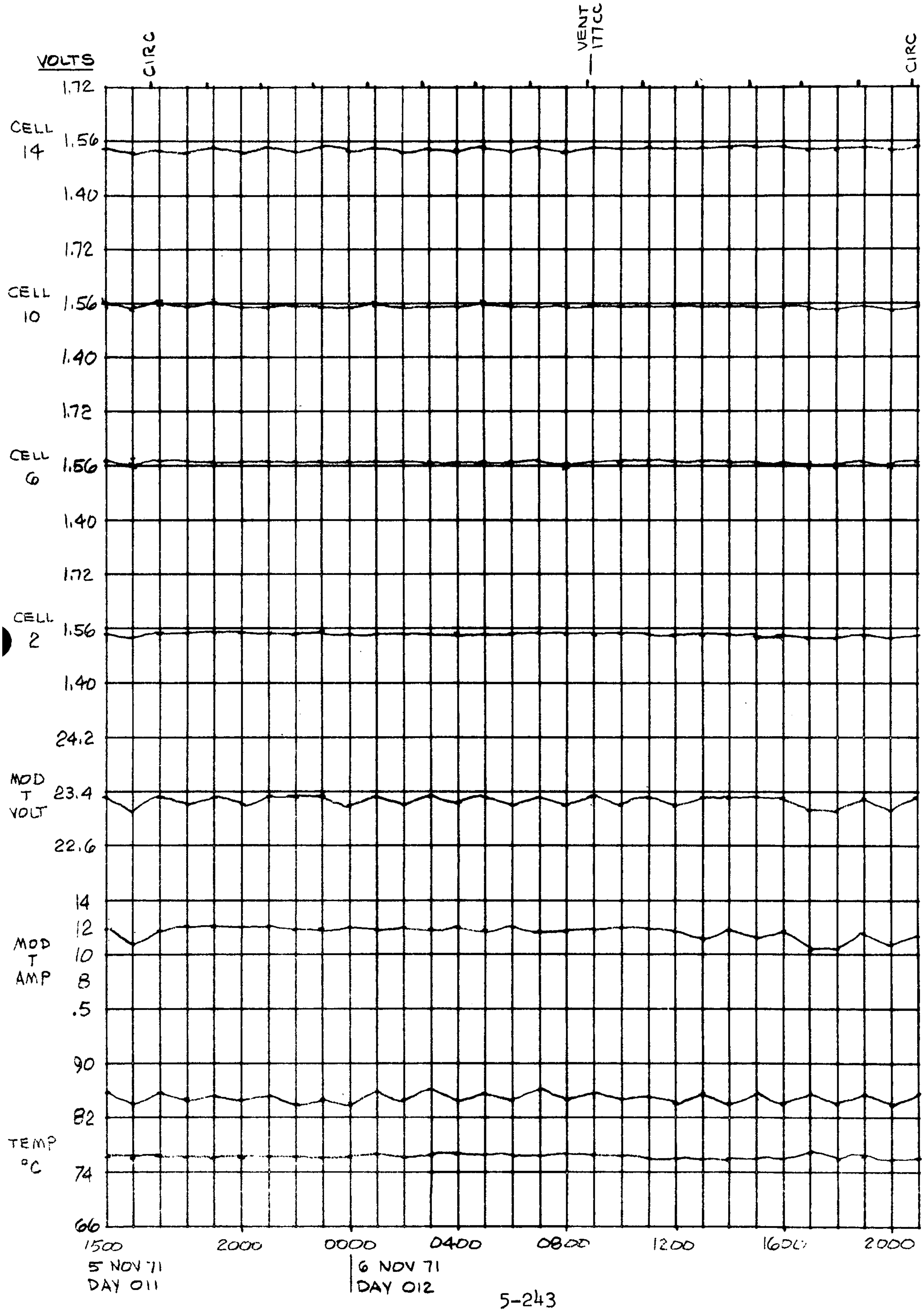


FIGURE 5-131 PERFORMANCE HISTORY (POSITION 1-MODULE 4)

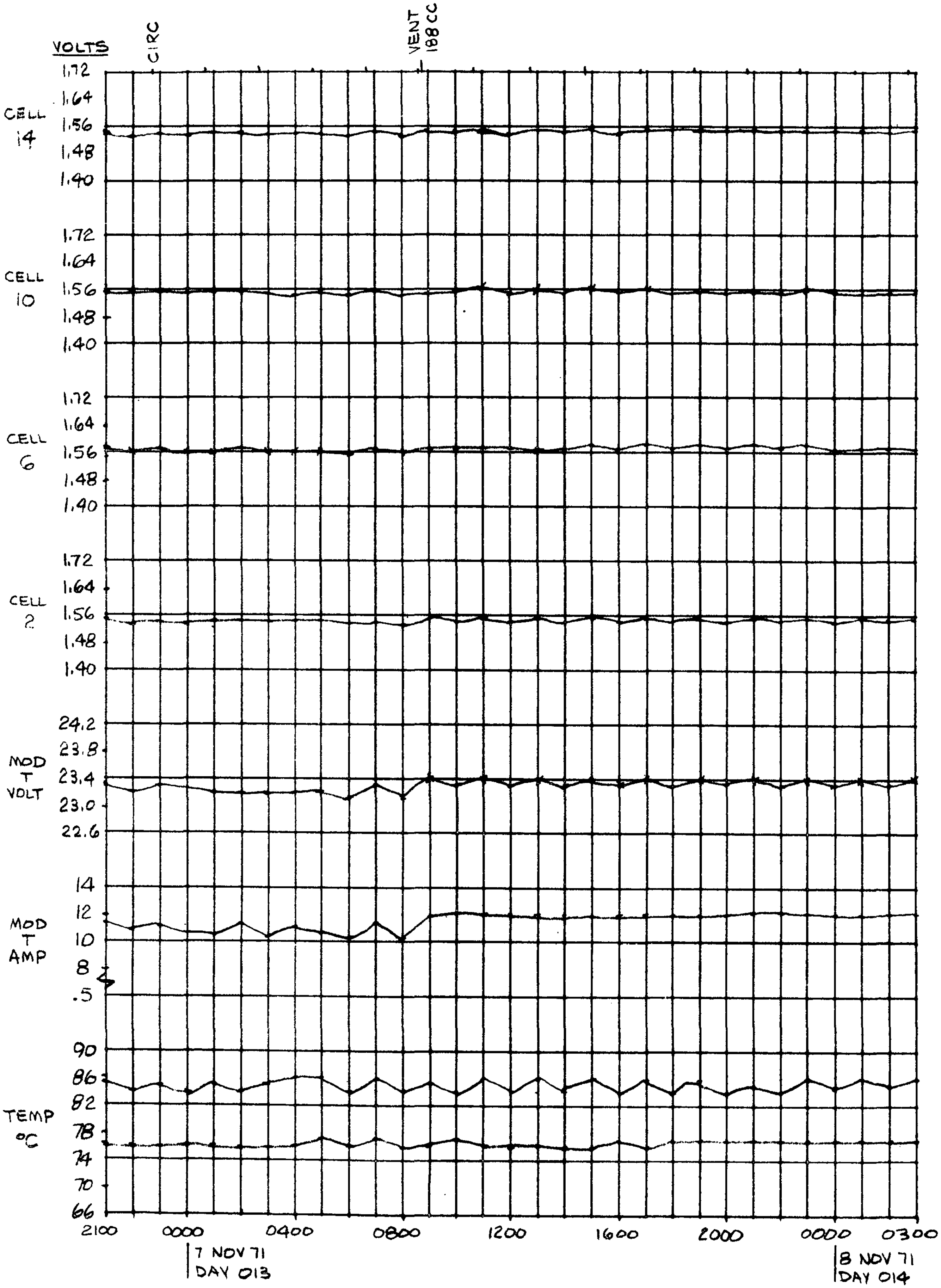


FIGURE 5-132 PERFORMANCE HISTORY (POSITION 1-MODULE 4)

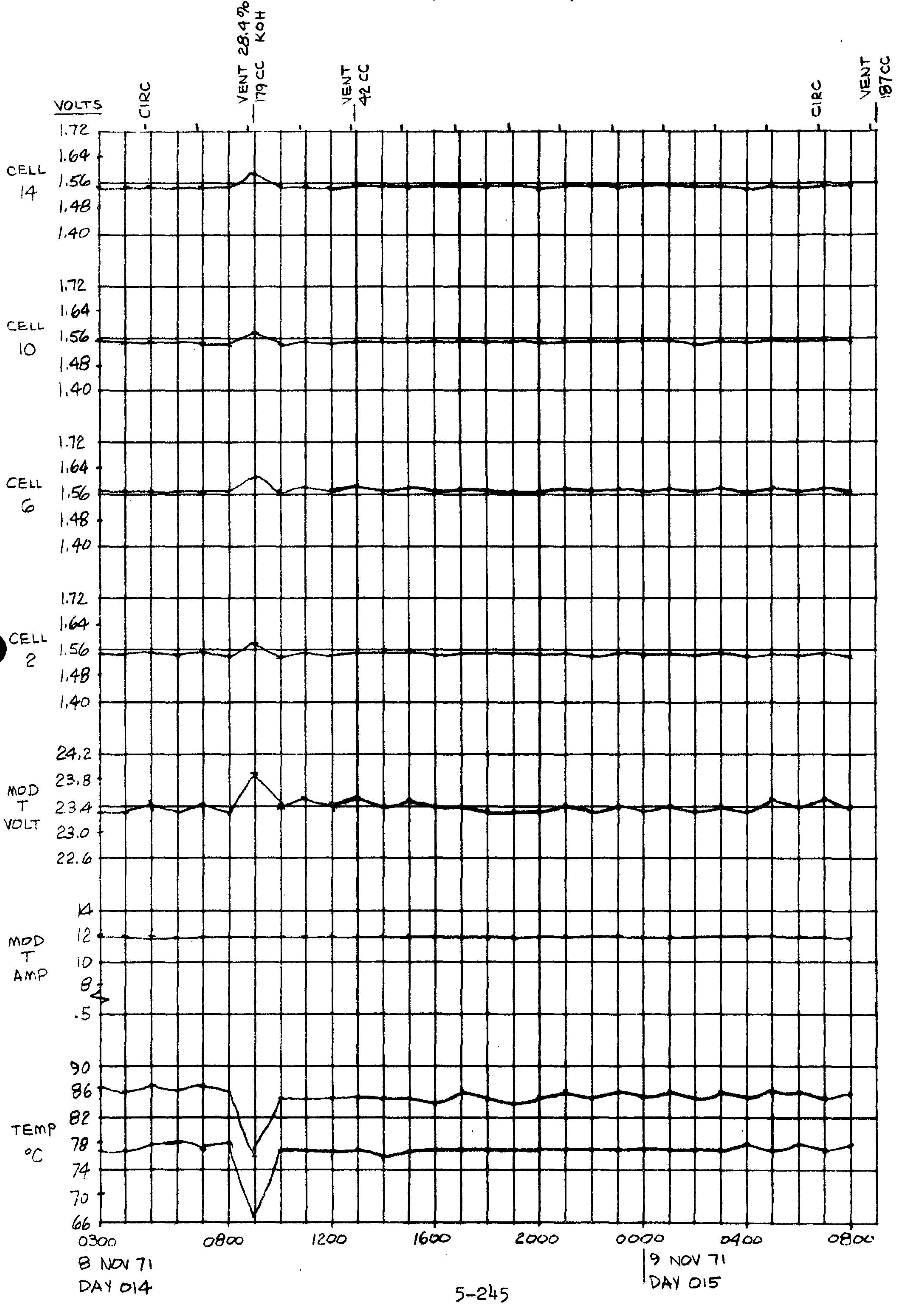


FIGURE 5-133 PERFORMANCE HISTORY (POSITION 1-MODULE 4)

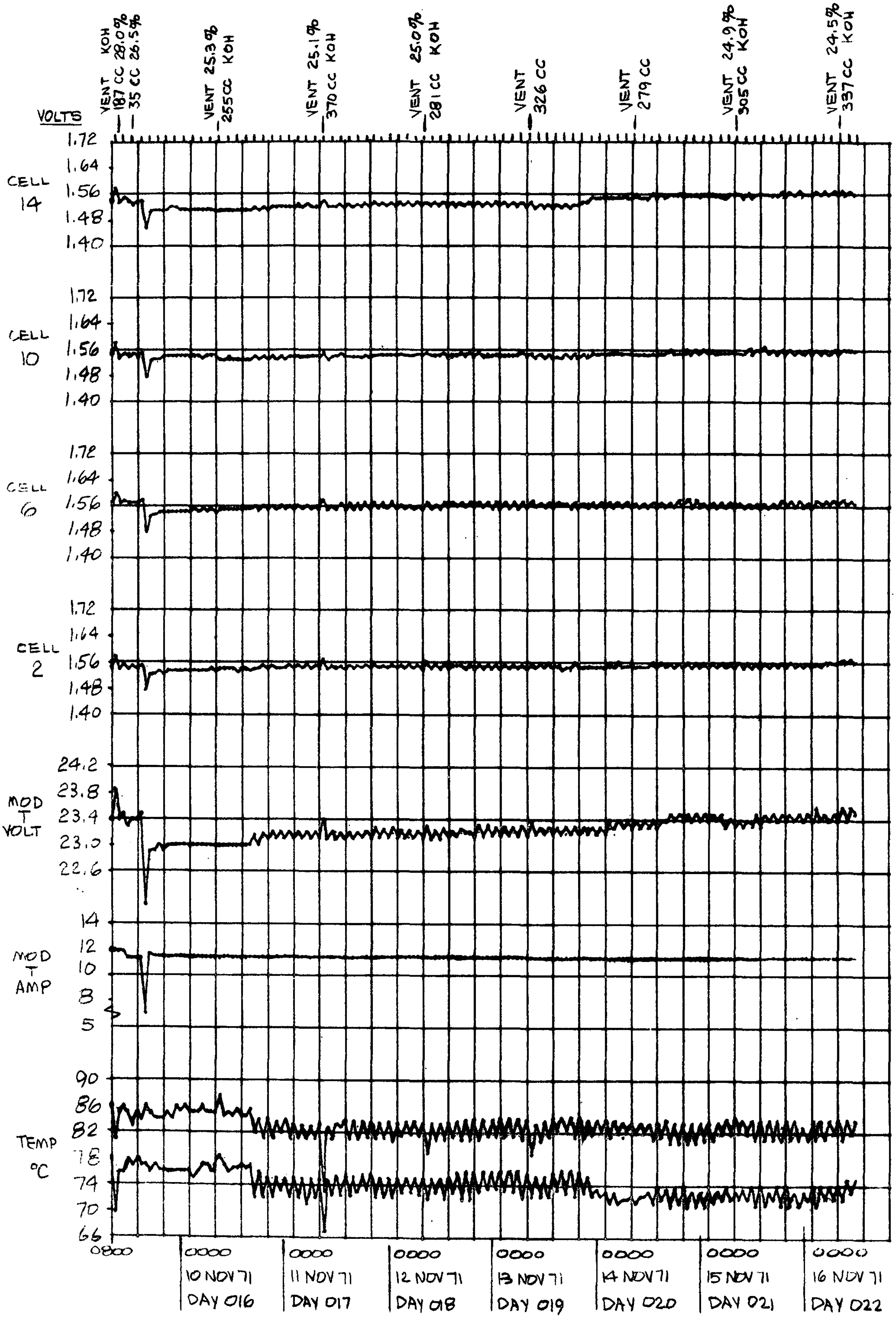


FIGURE 5-134 PERFORMANCE HISTORY (POSITION 1-MODULE 4)

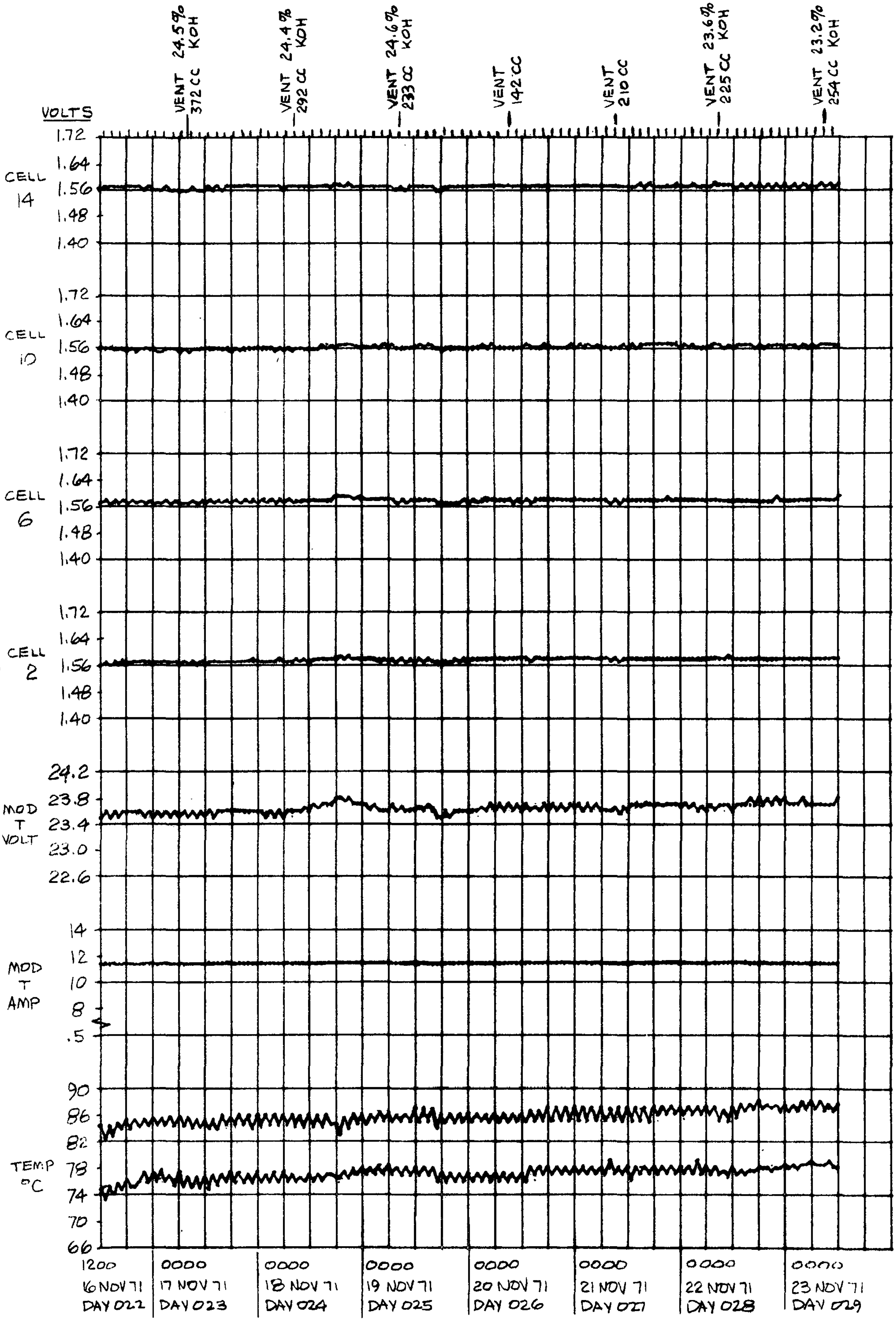


FIGURE 5-135 PERFORMANCE HISTORY (POSITION 1- MODULE 4)

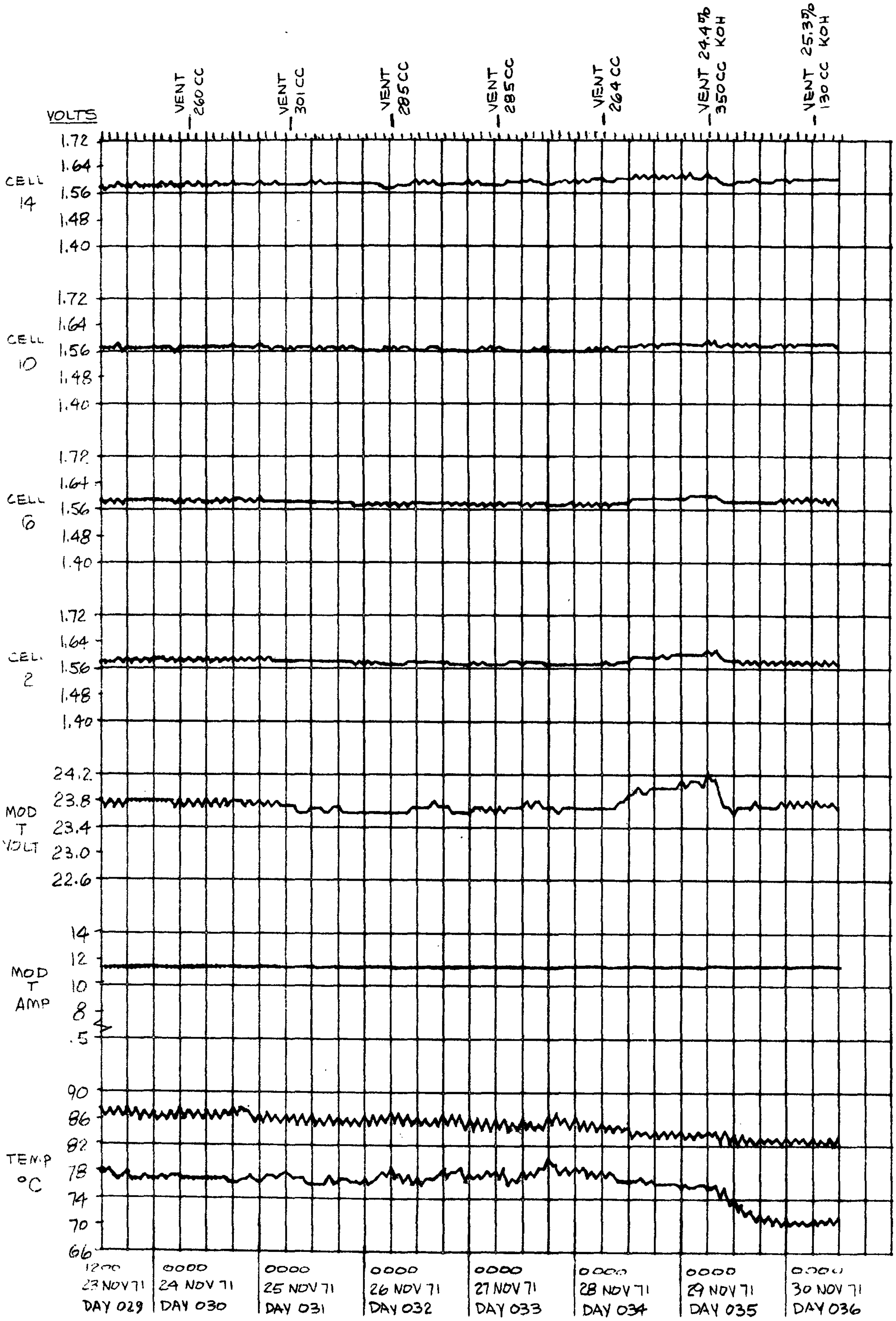
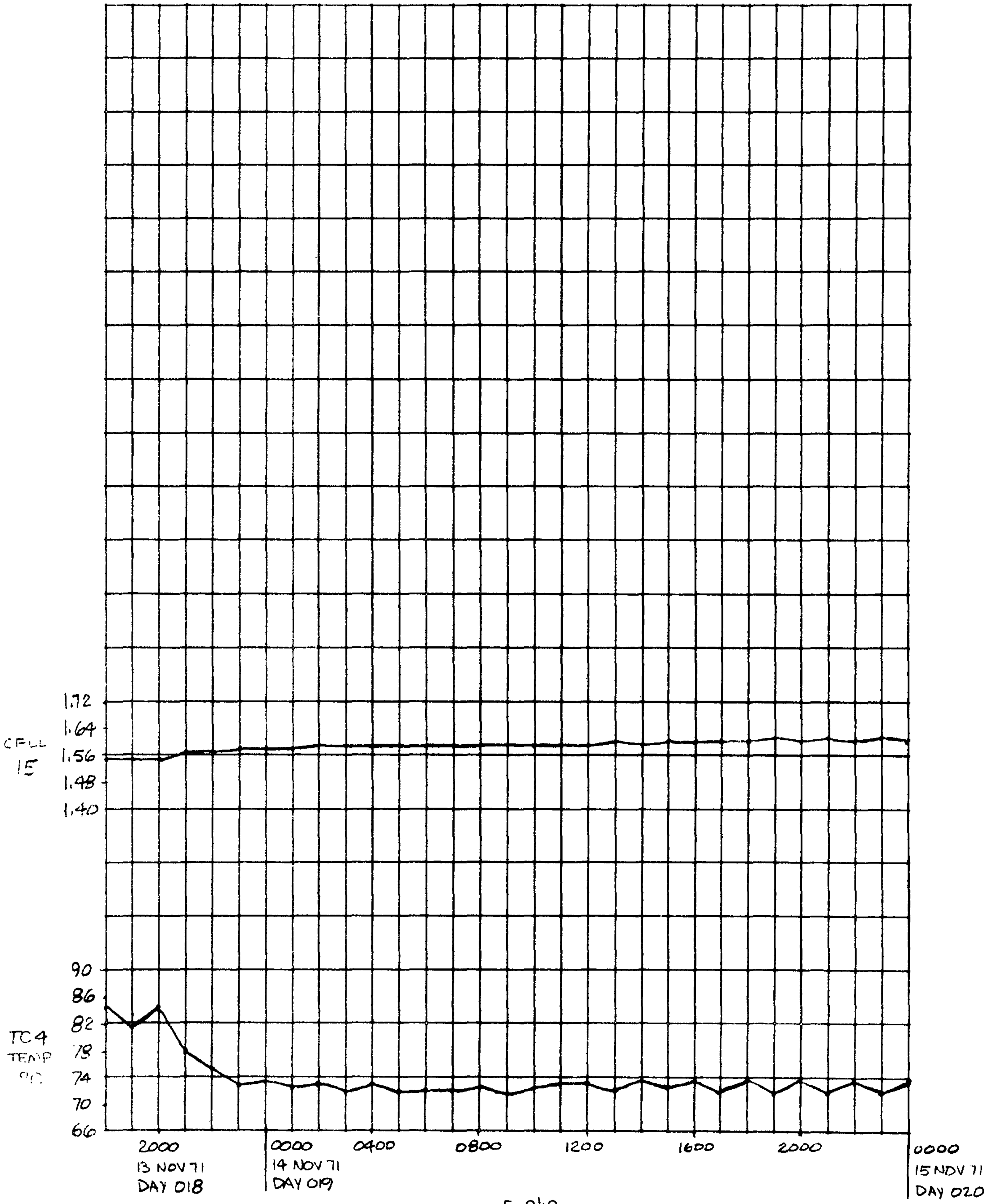


FIGURE 5-136 FAILURE OF END PLATE HEATER (POSITION 1- MODULE 4)

END PLATE HEATER NOT FUNCTIONING AFTER 2000 13 NOV 71 - CELL 15 SEEMS TO HAVE STABILIZED AT BETWEEN 1.60 AND 1.61. TC4 NOW ≈ EQUAL TO TC 3.



Figures 5-137 and 5-138 show the operating performance of the module from 30 November until failure. The momentary shutdown (about 10 seconds) on 3 December occurred because the computer dropped octal 1 and read 4 channels as being out of tolerance. Data was being taken at the time and it was evident that the channels were not out of tolerance.

The module continued operating until 2321 on 8 December at which time cell 1 went out of tolerance at 1.75 volts. Figure 5-139 shows the one minute data for 21 minutes preceding shutdown. A rapid rate of cell voltage increase started about 15 minutes before shutdown (1.64 to 1.70 volts) and one minute before shutdown the cell voltage jumped up at an even greater rate, from 1.70 to 1.75 in one minute. Module voltage did not change until the minute before shutdown. Module 4 was removed from the system 10 hours after shutdown and all cavities drained. The samples were analyzed and the results shown below:

H_2O cavity	150 cc's	23.4% KOH
H_2 cavity	38 cc's	22.6% KOH
O_2 cavity	Zero liquid	No Concentration Readings

System sample of electrolyte measured at 22.9% KOH.

An inspection of the outside of the module after all the KOH had been removed indicated:

- rear end plate heater wire disconnected
- heater tabs cell 1 through 5, 8, 13 and 15 corroded off
- power lead to cell 1 screen not attached to screen
- instrumentation wire not attached to cell 1 screen

Based on the above conditions it is suspected that the cell did not go out of tolerance but only that the instrumentation wire contact resistance increased, because of poor contact, to give an indication of an out of tolerance cell. A pressurecheck for external leaks indicated a number of leaks.

FIGURE 5·137 PERFORMANCE HISTORY (POSITION 1 - MODULE 4)

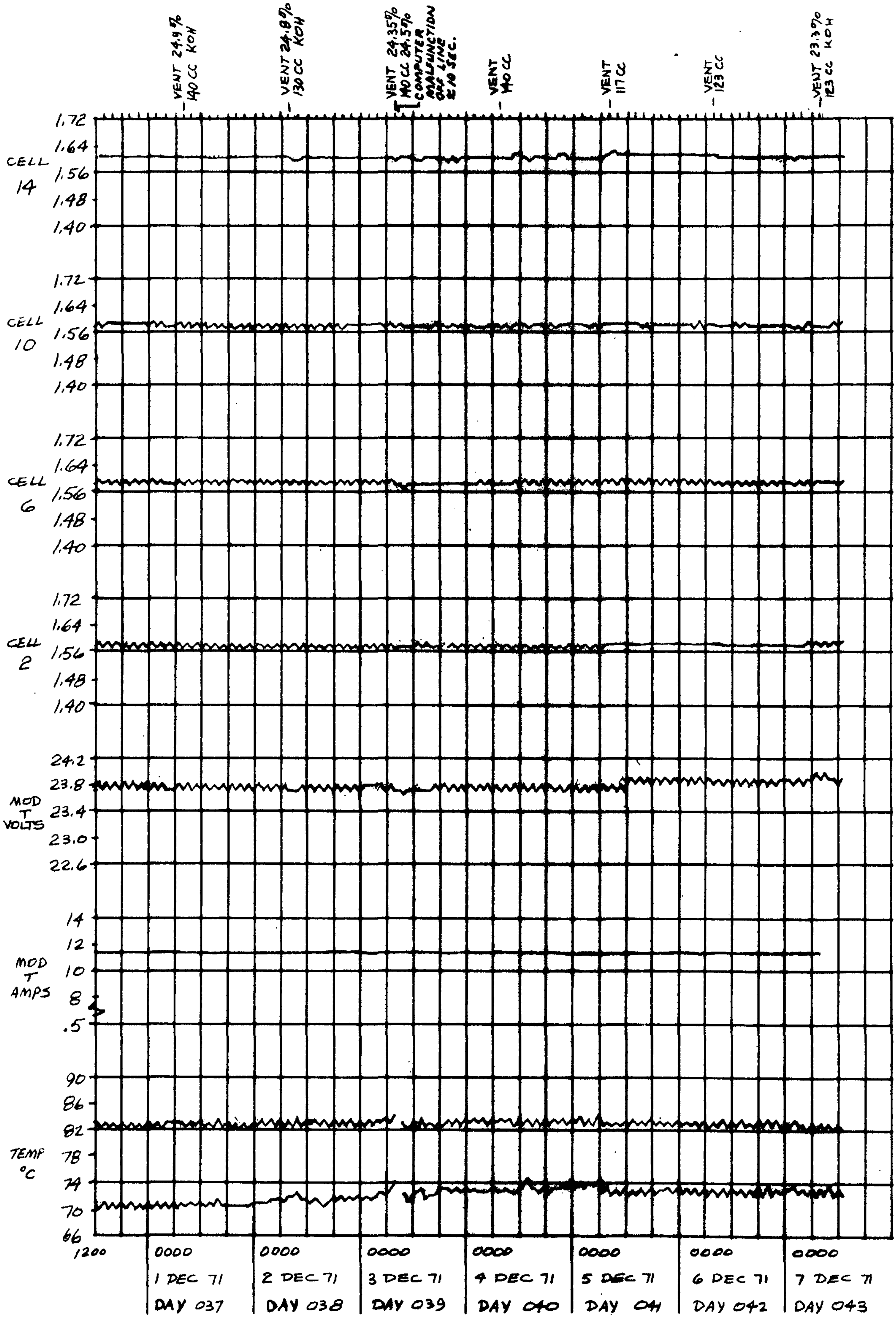


FIGURE 5-138 PERFORMANCE HISTORY (POSITION 1-MODULE 4)

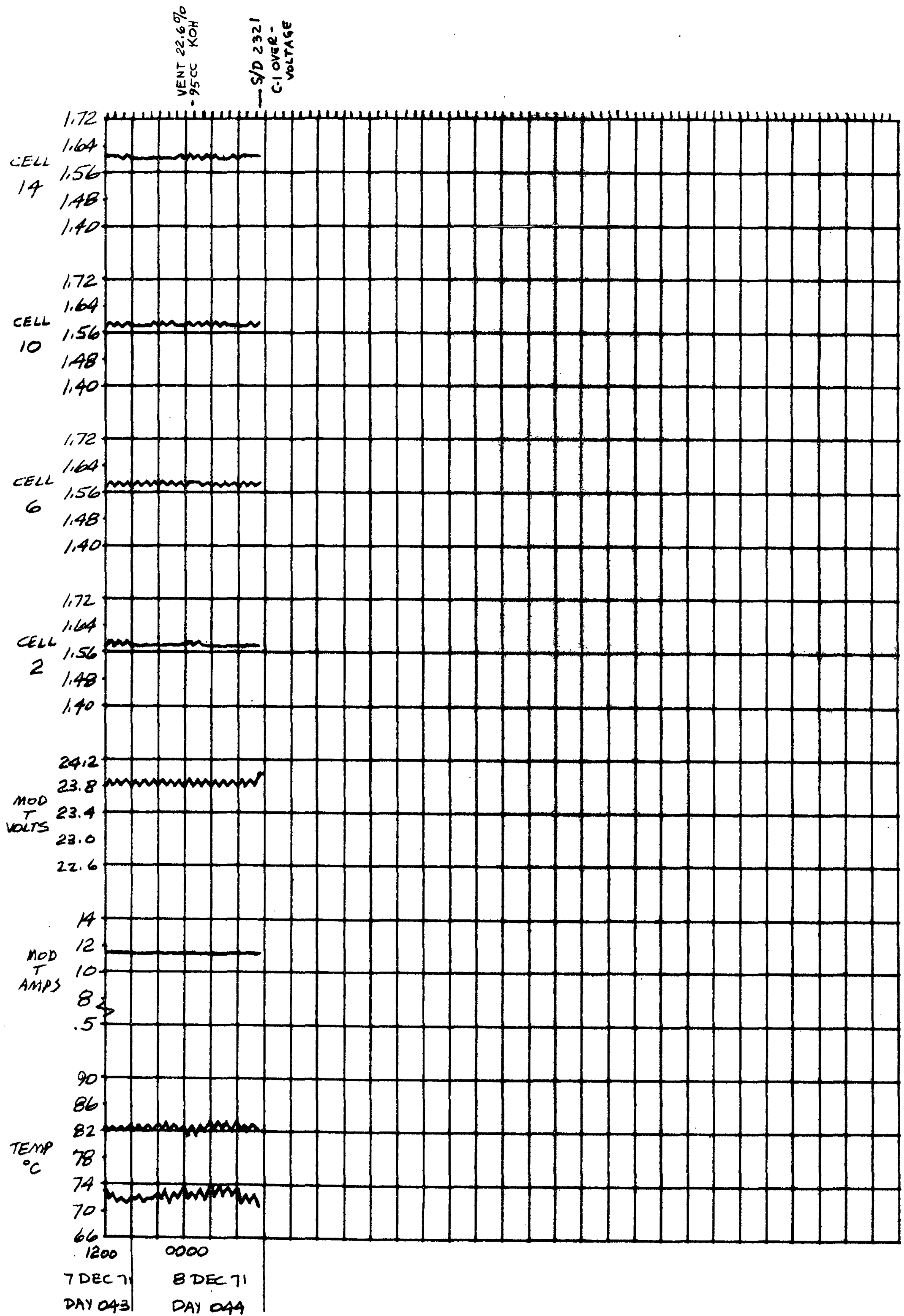
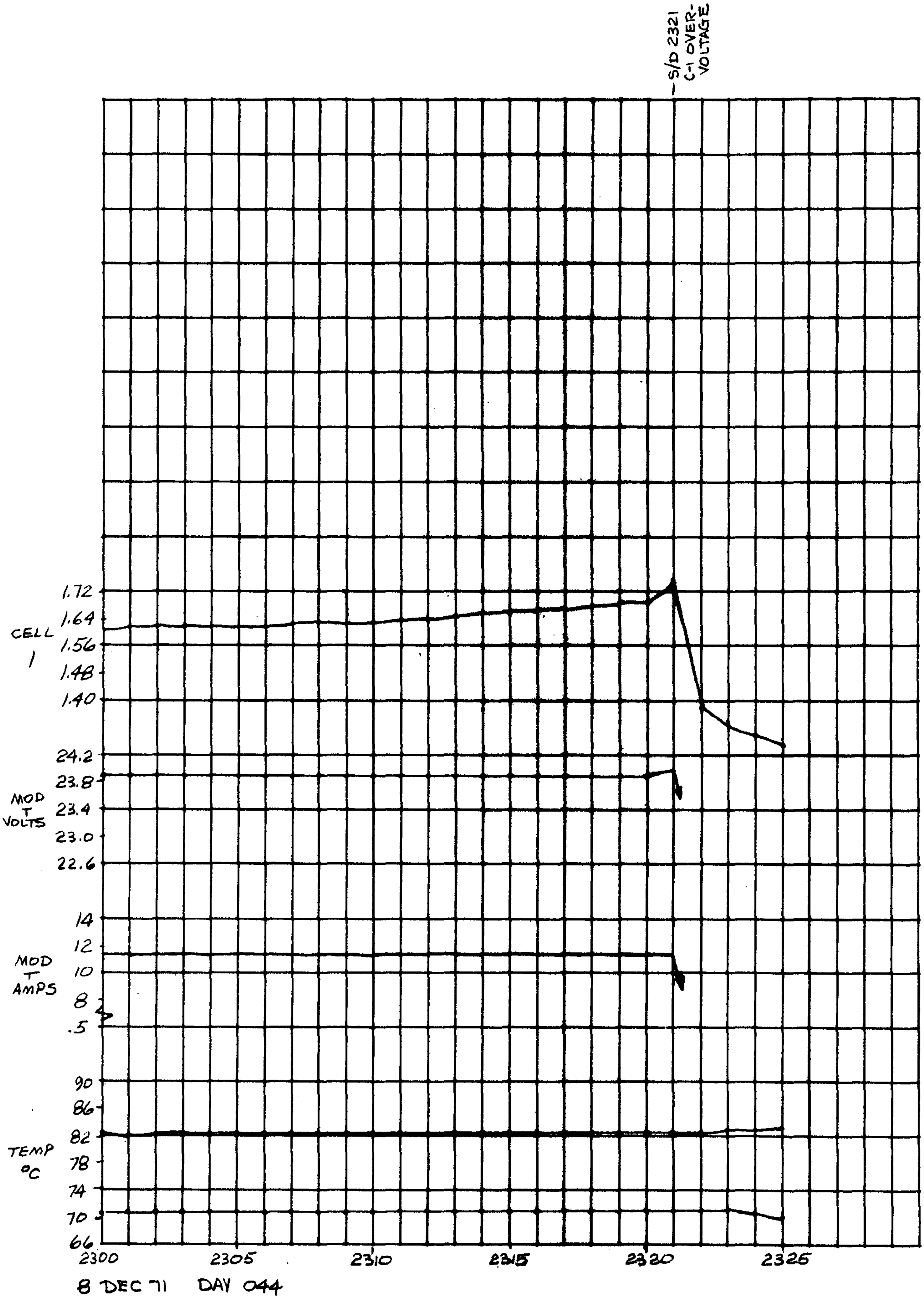


FIGURE 5·139 PERFORMANCE HISTORY (POSITION 1 - MODULE 4)



Breakaway bolt torques on the module were between 3.95 and 5.65 N.m (35 and 50 inch pounds). After increasing the torque to 8.45 N/m (75 inch pounds), the module was rechecked. Leaks still occurred and it was decided to disassemble the module.

Each cell of this module was checked for external leaks. Seven cells were found to have leaks. All of these cells showed the same kind of leakage that was found in the cells of module 1; hairline cracks around the matrix periphery as well as between the H_2O manifold and the outside diameter of the o-ring groove. Further review of available data indicated that this module had developed an undesirable salt bridge between the H_2 electrode and the water cavity. As a result, the decision was made by the test committee not to use this design module in future testing. The salt bridge problem appeared to be caused by one or both of the following reasons: a) no KOH barrier (Zitex sheet) existed between the water matrix and the hydrogen gas cavity, thus KOH could be carried over into the hydrogen cavity during water vapor transfer and/or b) the hydrogen electrode in the cells of this module was a porous nickel plaque which had a tendency to weep, thus allowing KOH to seep back from the cathode and the electrolyte matrix to form a KOH bridge in the bottom of the hydrogen cavity. The magnitude of this bridge was enhanced by the fact that KOH was leaking back into the water cavity through the leaking check valves at the outlet of the module.

5.7.2.5 Module 5

Figure 5-140 through 5-149 show the detailed performance of this module during the period 21 October and 2 November 1971. This module has operated at higher module voltage than any other module. A comparison with the LSI acceptance test data verifies that the high module voltage was typical of the module (see Figure 5-12). The module operated from 1630 on 22 October to 0930 on 28 October 1971 with uniform performance and only a slight trend upward of the voltage of a few cells. The module was shutdown to change its position from 3 to 2 in the system. This was done to determine if position in the system would change the performance of a module. Module 3 was installed in position 3 at this time also. Module 5 was off only about 15 minutes to

FIGURE 5-140 PERFORMANCE HISTORY (POSITION 3-MODULE 5)

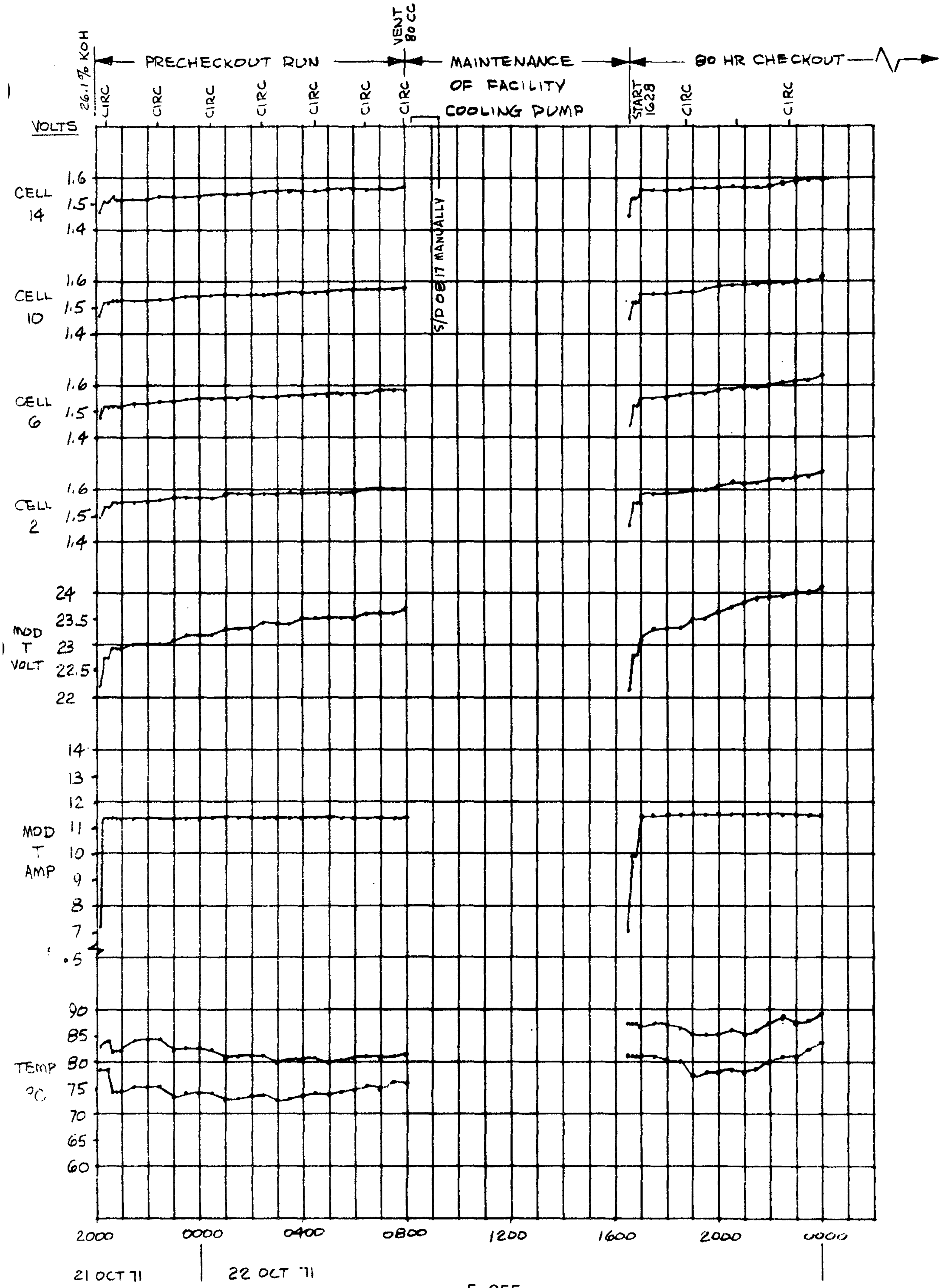


FIGURE 5-141 PERFORMANCE HISTORY (POSITION 3-MODULE 5)

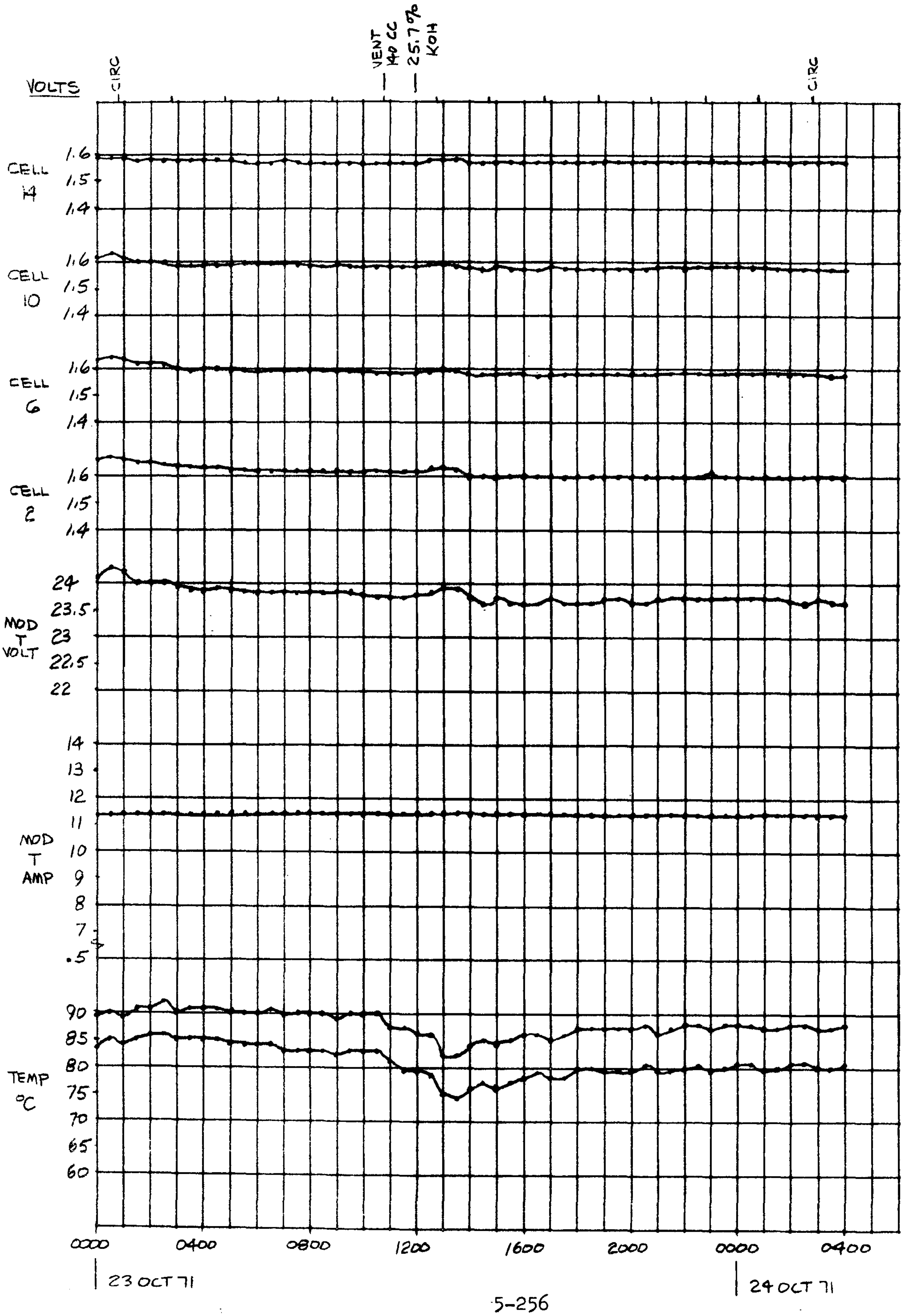


FIGURE 5-142 PERFORMANCE HISTORY (POSITION 3 - MODULE 5)

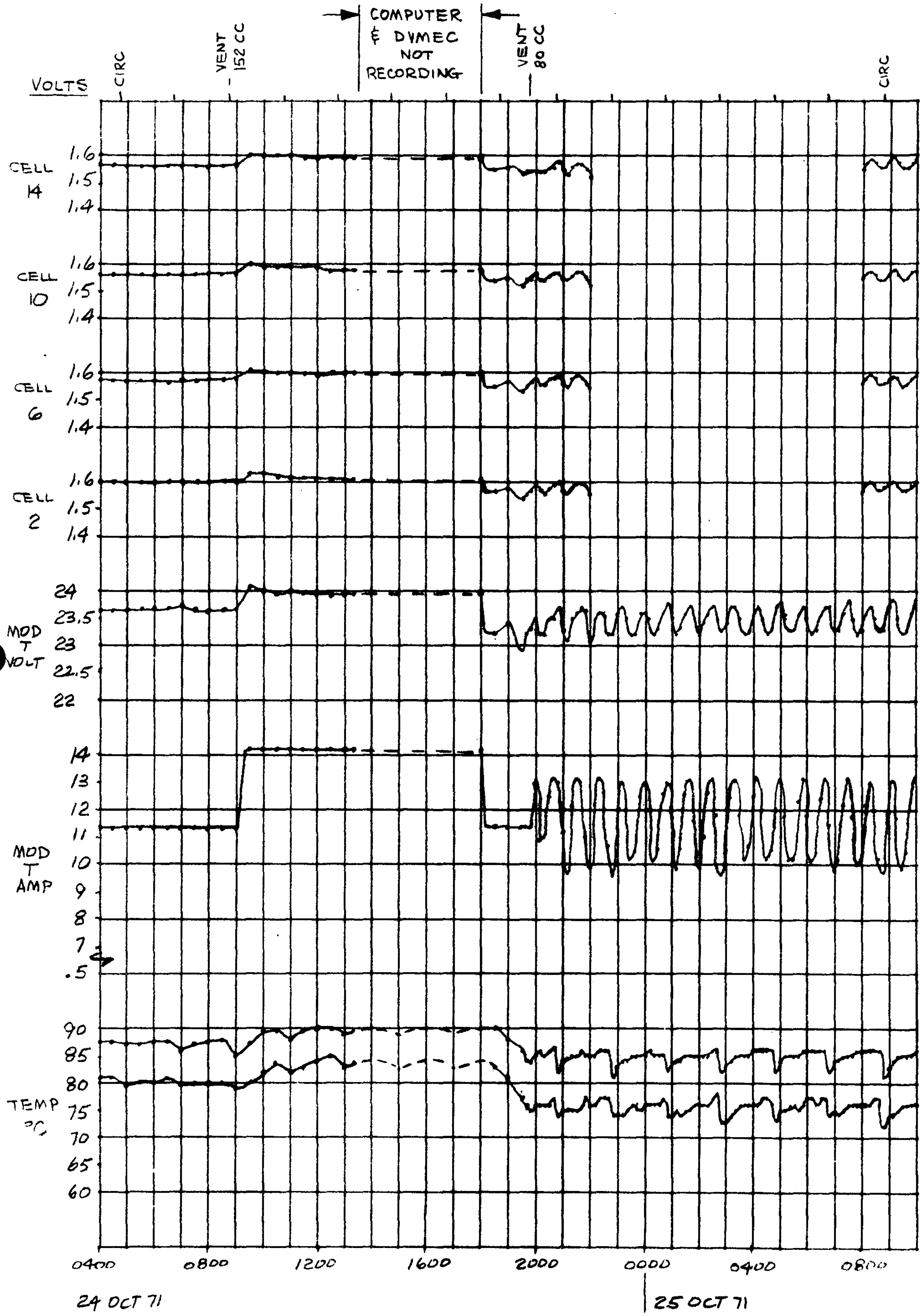


FIGURE 5-143 PERFORMANCE HISTORY (POSITION 3-MODULE 5)

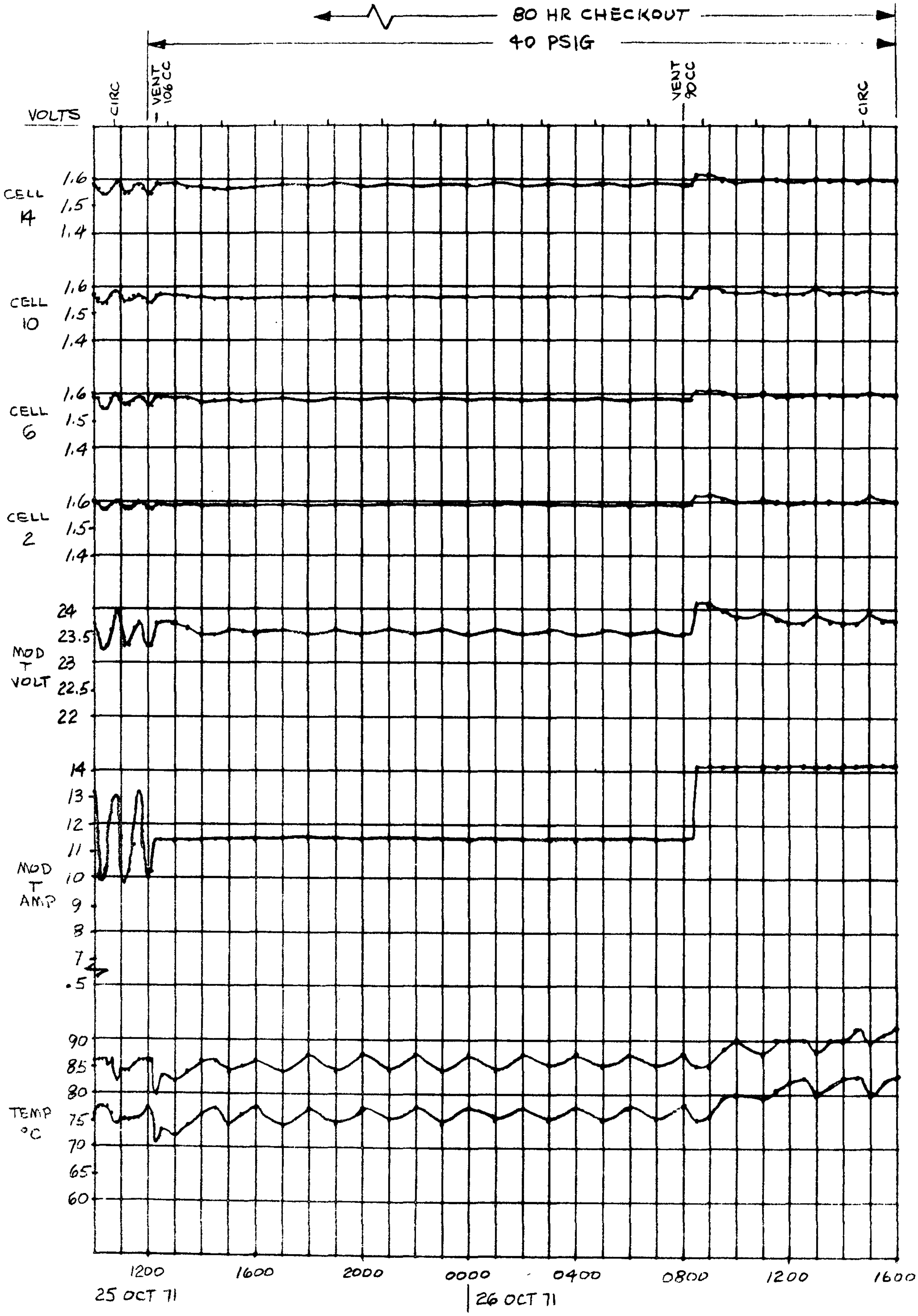


FIGURE 5-144 PERFORMANCE HISTORY (POSITION 3-MODULE 5)

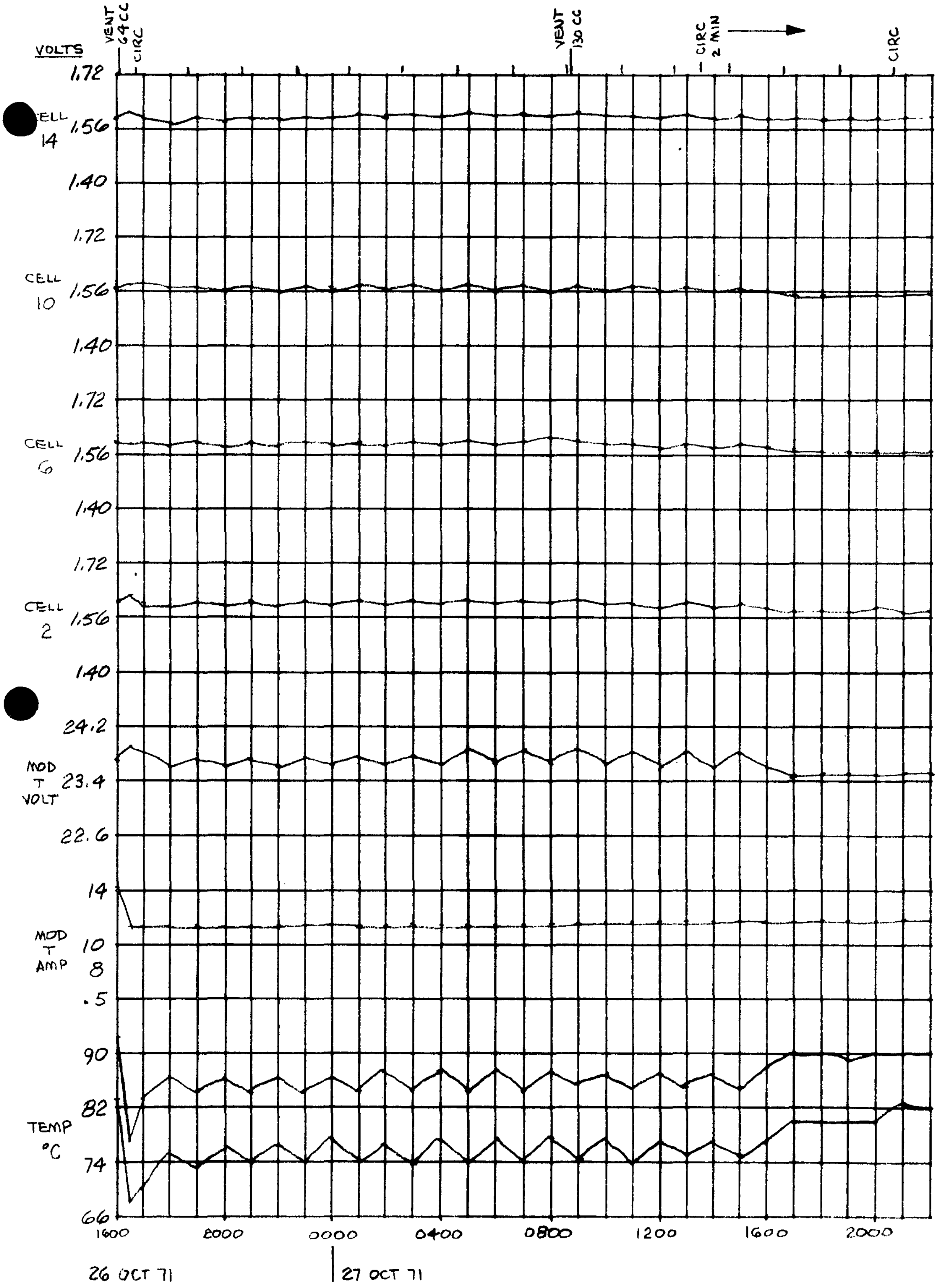


FIGURE 5-145 PERFORMANCE HISTORY

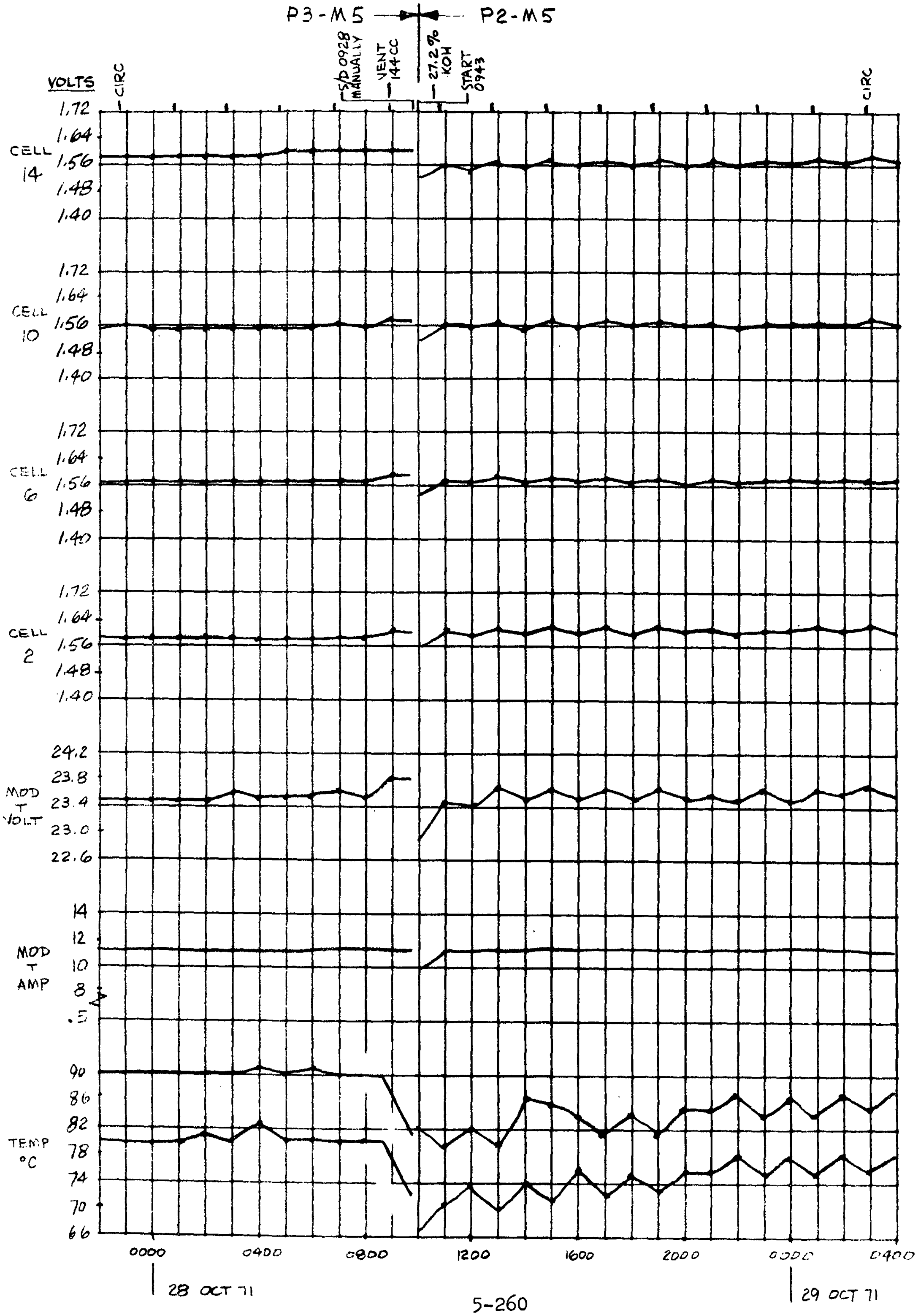


FIGURE 5-146 PERFORMANCE HISTORY (POSITION 2-MODULE 5)

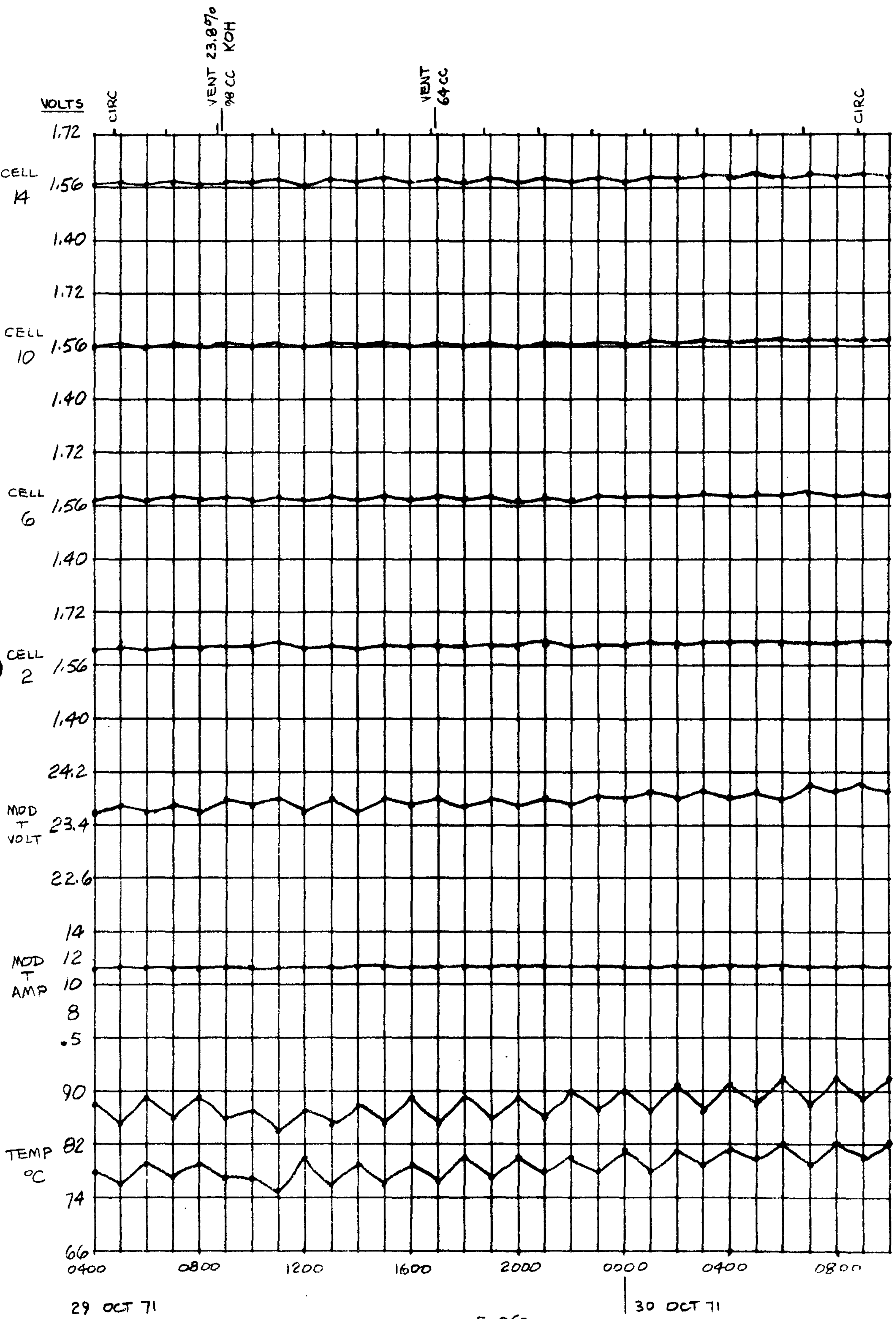


FIGURE 5-147 PERFORMANCE HISTORY

(POSITION 2-MODULE 5)

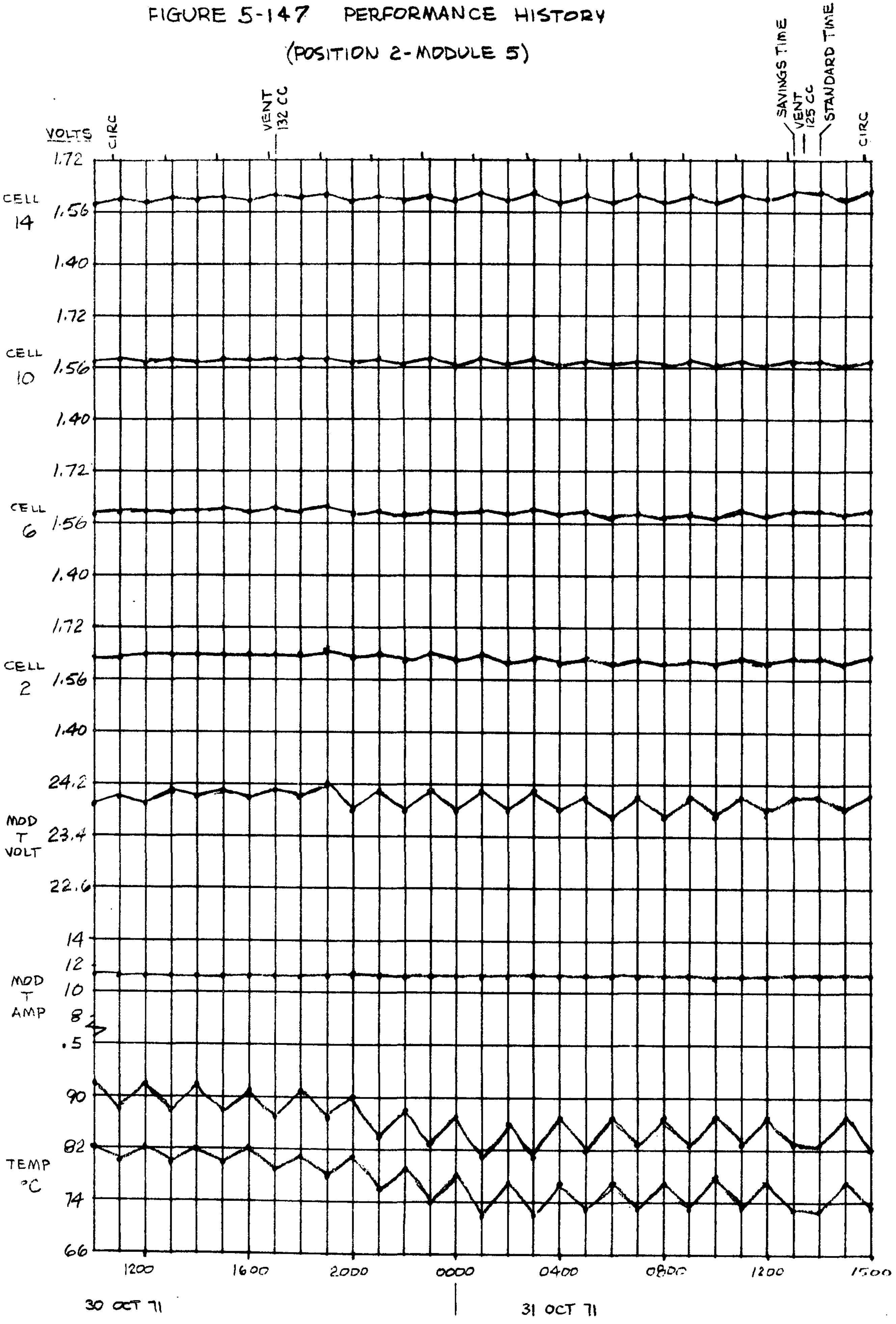


FIGURE 5-148 PERFORMANCE HISTORY (POSITION 2-MODULE 5)

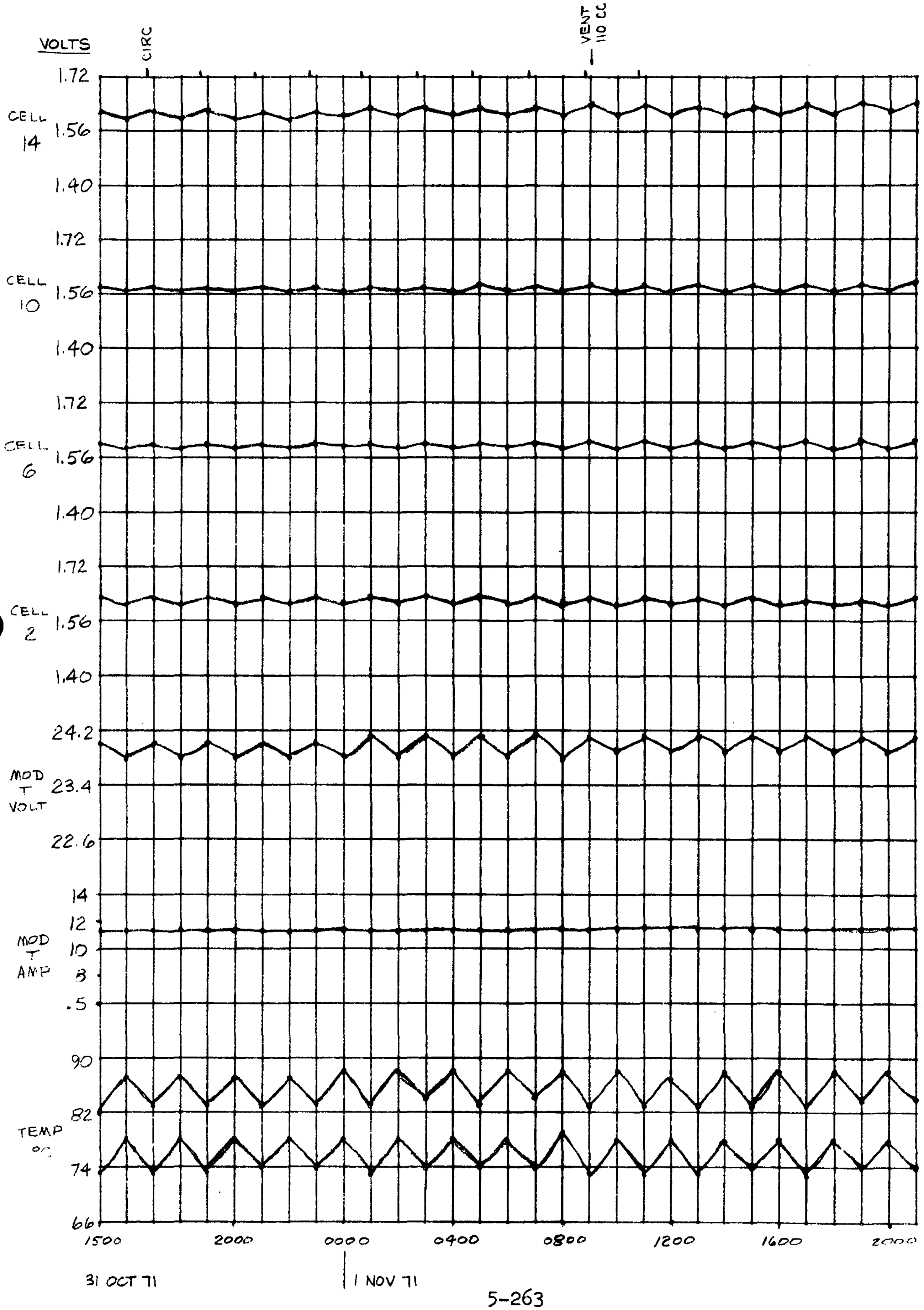
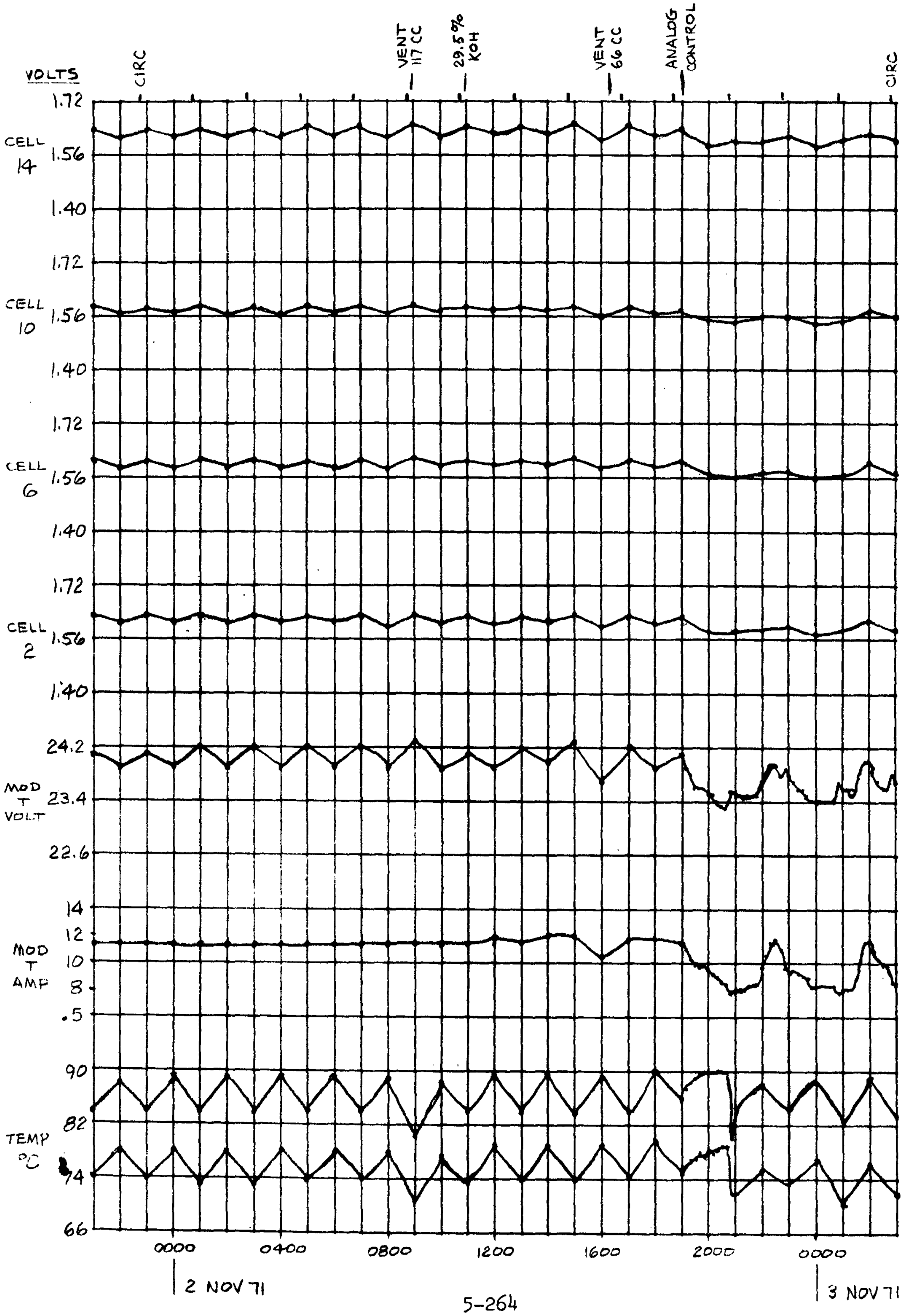


FIGURE 5-149 PERFORMANCE HISTORY (POSITION 2-MODULE 5)



make the change and when restarted, returned to its original operating condition within 2 hours. After that change, the module operated steady with a slight rise in module voltage for about 100 hours; i.e., the voltage increased from 23.6 to 24.1 volts. Average temperature within the module remainded essentially constant. Cell 14 voltage showed a gradual increase from 1.57 to 1.65. Voltage rise of the other cells was a much slower rate during the same period of time.

The module operated on analog control between 3 and 5 November as indicated on Figure 5-150 and 5-151. The strange current readings on 5 November were due to high module voltage and an attempt by the operators to obtain the 3 to 4 hour analog cycle desired. The module failed at 1012 on 7 November due to over-temperature condition. After 4 hours on the flush cart the concentration of electrolyte in the flush cart reservoir had not changed more than 0.2%. No problems were apparent on the module and it was considered ready to be reinstalled in the system. This was done at noon on 9 November. Performance of the module after 6 November is shown on Figure 5-152 through 5-156. Again module voltage gradually increased with time and decreasing system electrolyte concentration until 0613 on 29 November when cell 13 went out of tolerance at 1.75 volts. Operation of this module was essentially continuous for about 20 days (473 hours). Visual inspection of the module after failure indicated a moderate amount of KOH on cells 5 through 15 heater tabs and a leak at cell 14 and 15. Bolt torques were very low - between 1.69 and 3.38 N.m (15 and 30 inch pounds). There was no external evidence as to why cell 13 went out of tolerance. Internally, there could have been a restriction to water feed thus causing matrix drying. This module was repaired and made ready for reuse. The module was not reused because there was evidence in the data that indicated salt bridging had developed in the 1970 design modules. The data indicated that salt bridging had definitely developed in module 4, but module 5 had not operated alone long enough to conclusively prove that salt bridging had developed there also. However, the decision was made to stop using the 1970 design modules in this test program.

FIGURE 5-150 PERFORMANCE HISTORY (POSITION 2-MODULE 5)

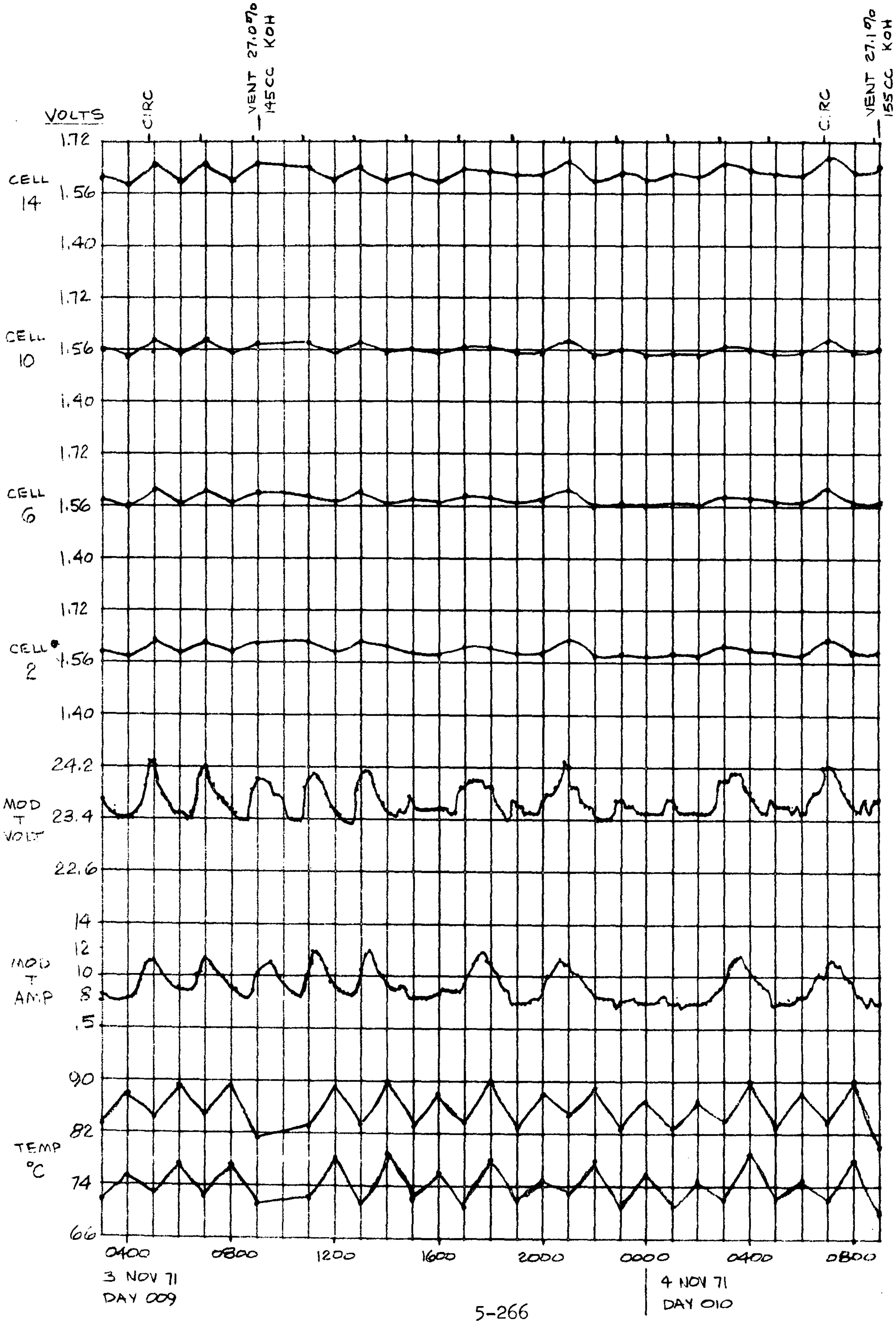


FIGURE 5-151 PERFORMANCE HISTORY (POSITION 2- MODULE 5)

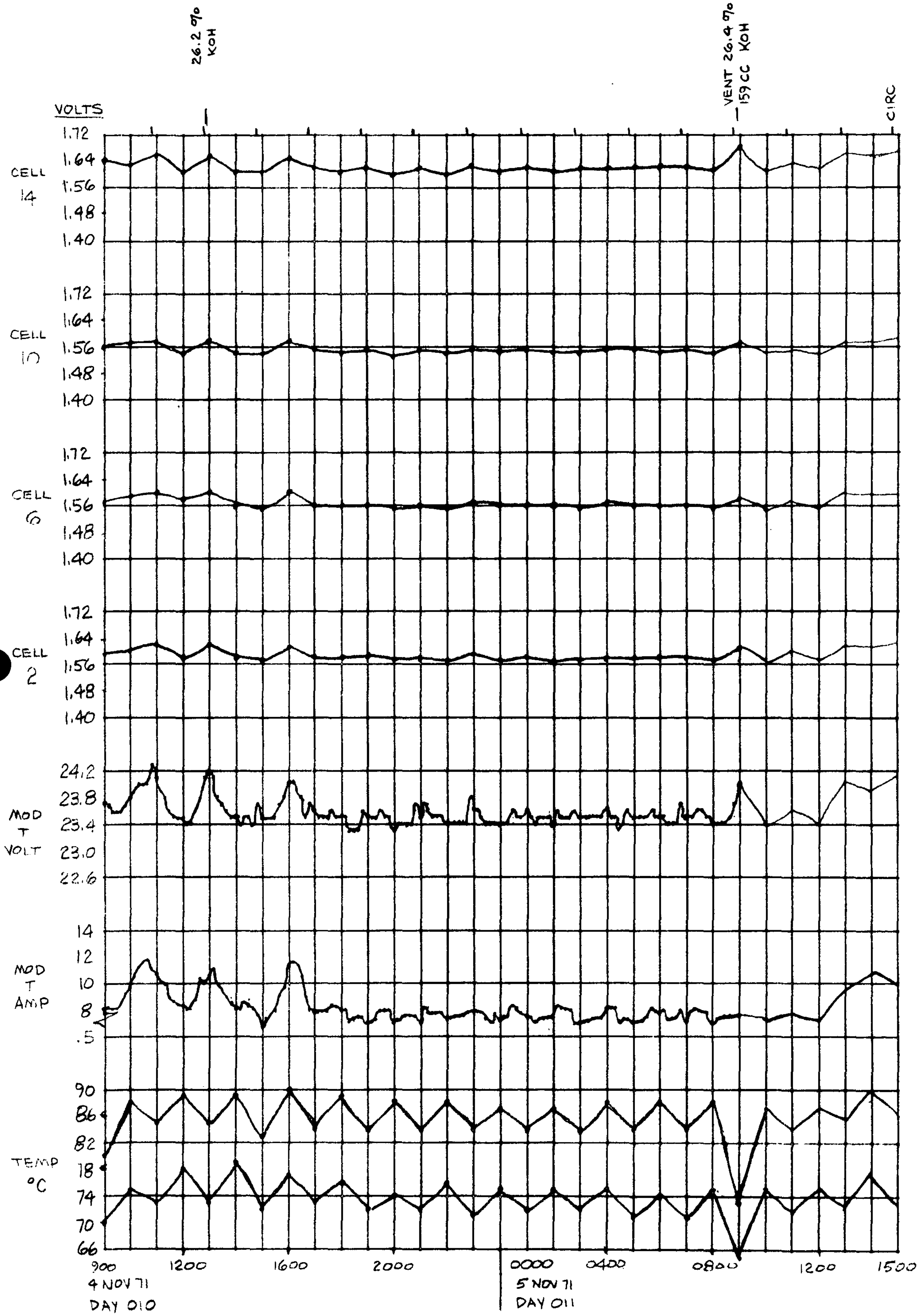


FIGURE 5-152 PERFORMANCE HISTORY (POSITION 2-MODULE 5)

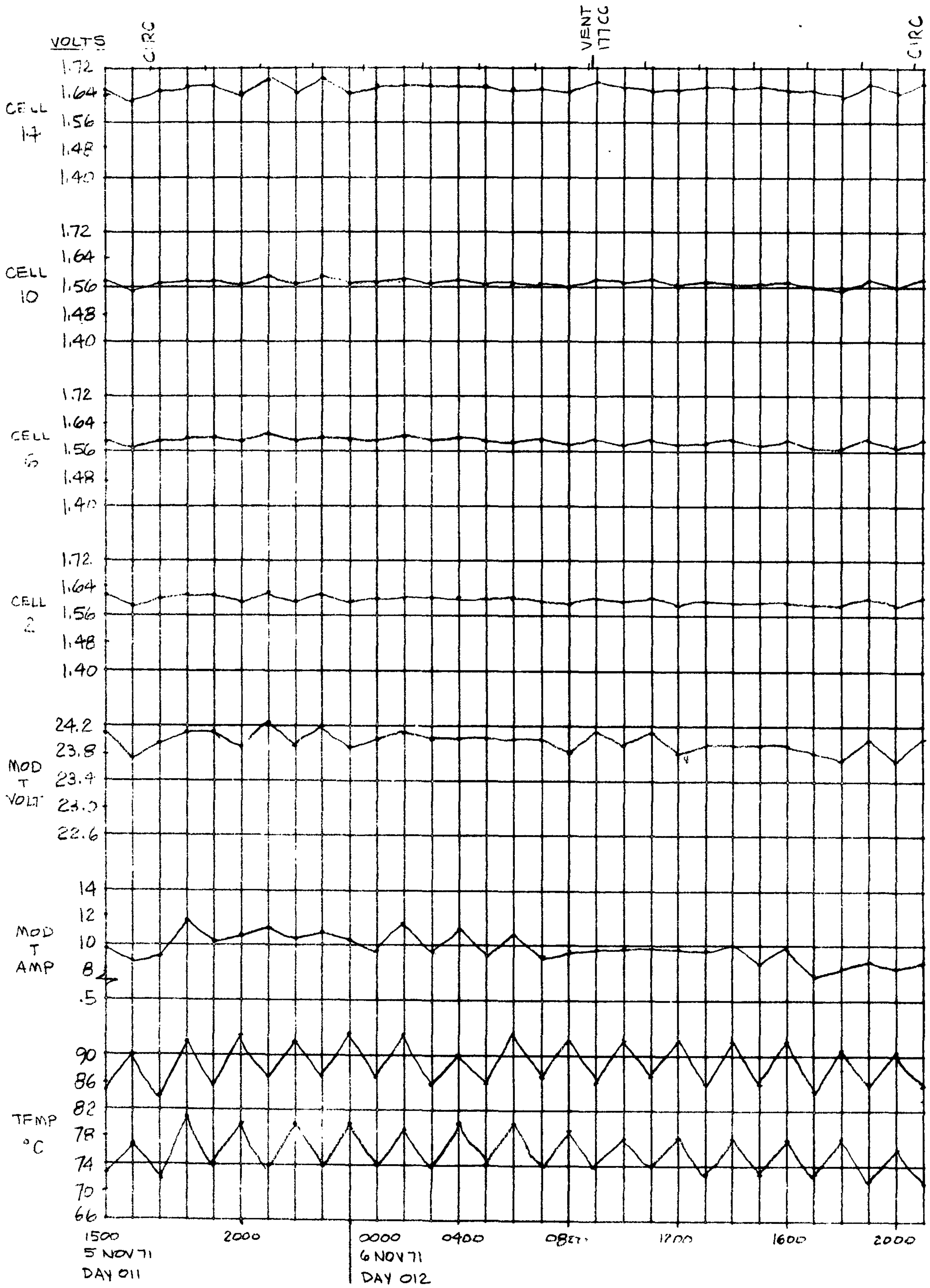


FIGURE 5-153 PERFORMANCE HISTORY (POSITION 2-MODULE 5)

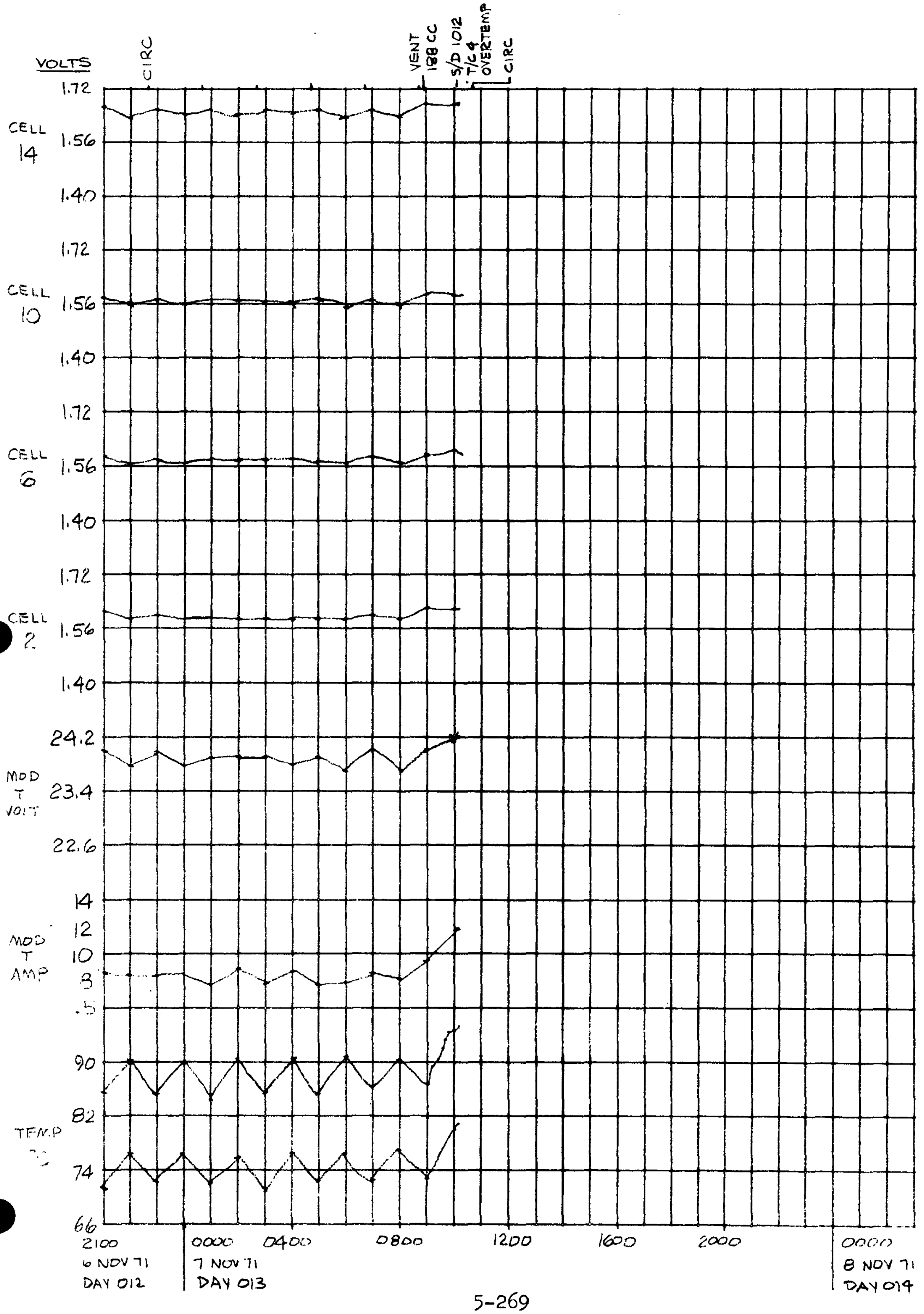


FIGURE 5-154 PERFORMANCE HISTORY (POSITION 3 - MODULE 5)

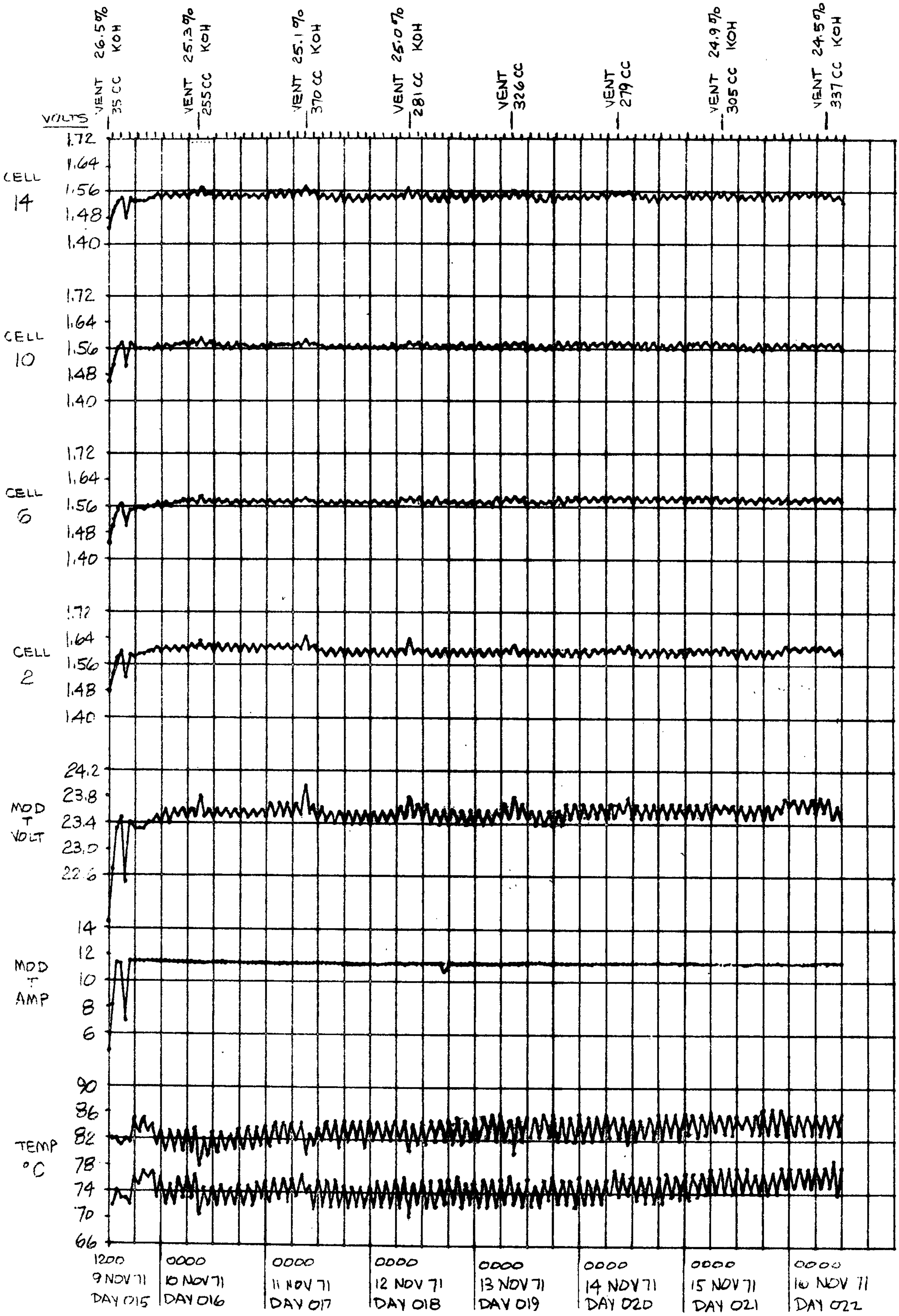


FIGURE 5-155 PERFORMANCE HISTORY (POSITION 3-MODULE 5)

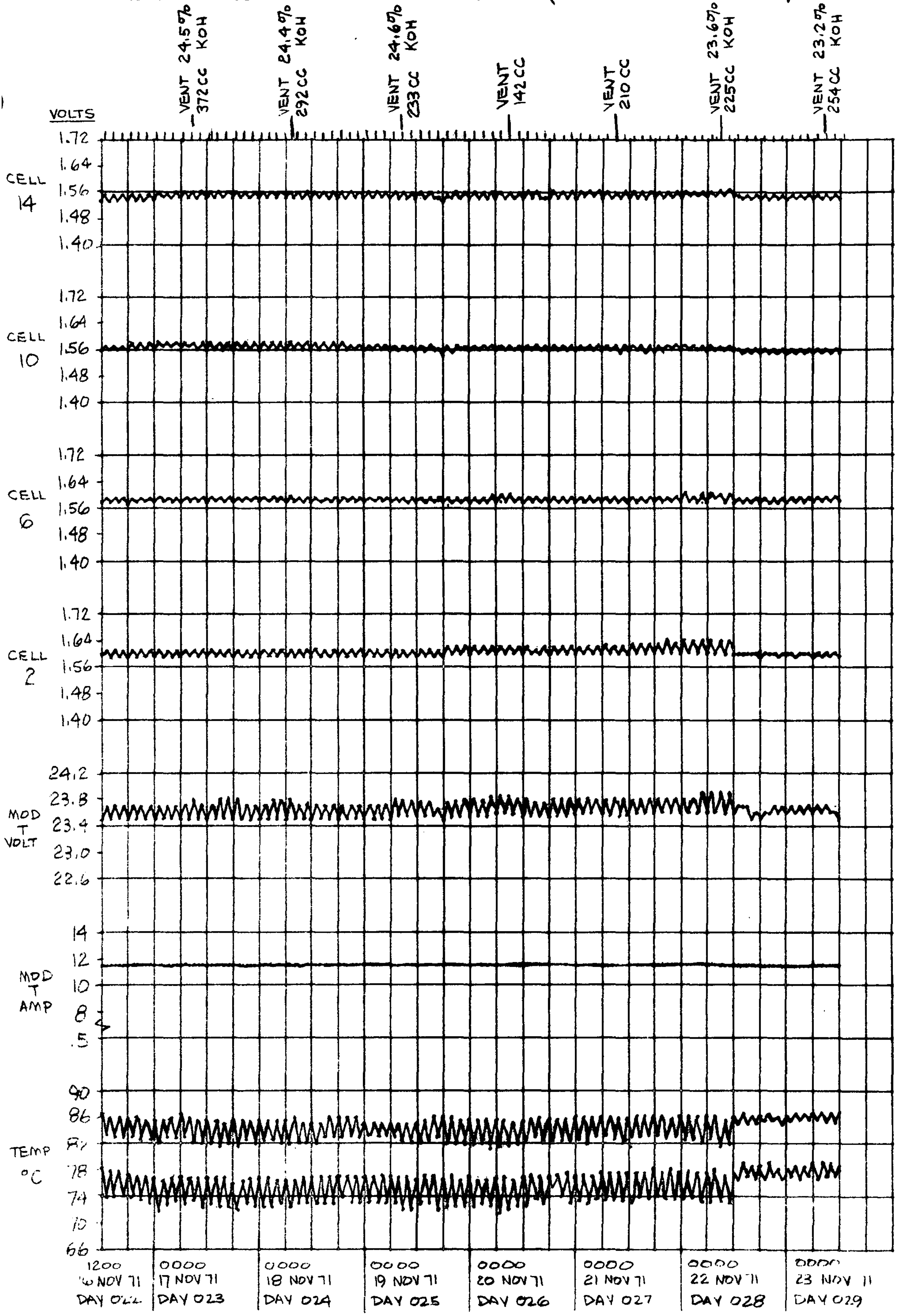
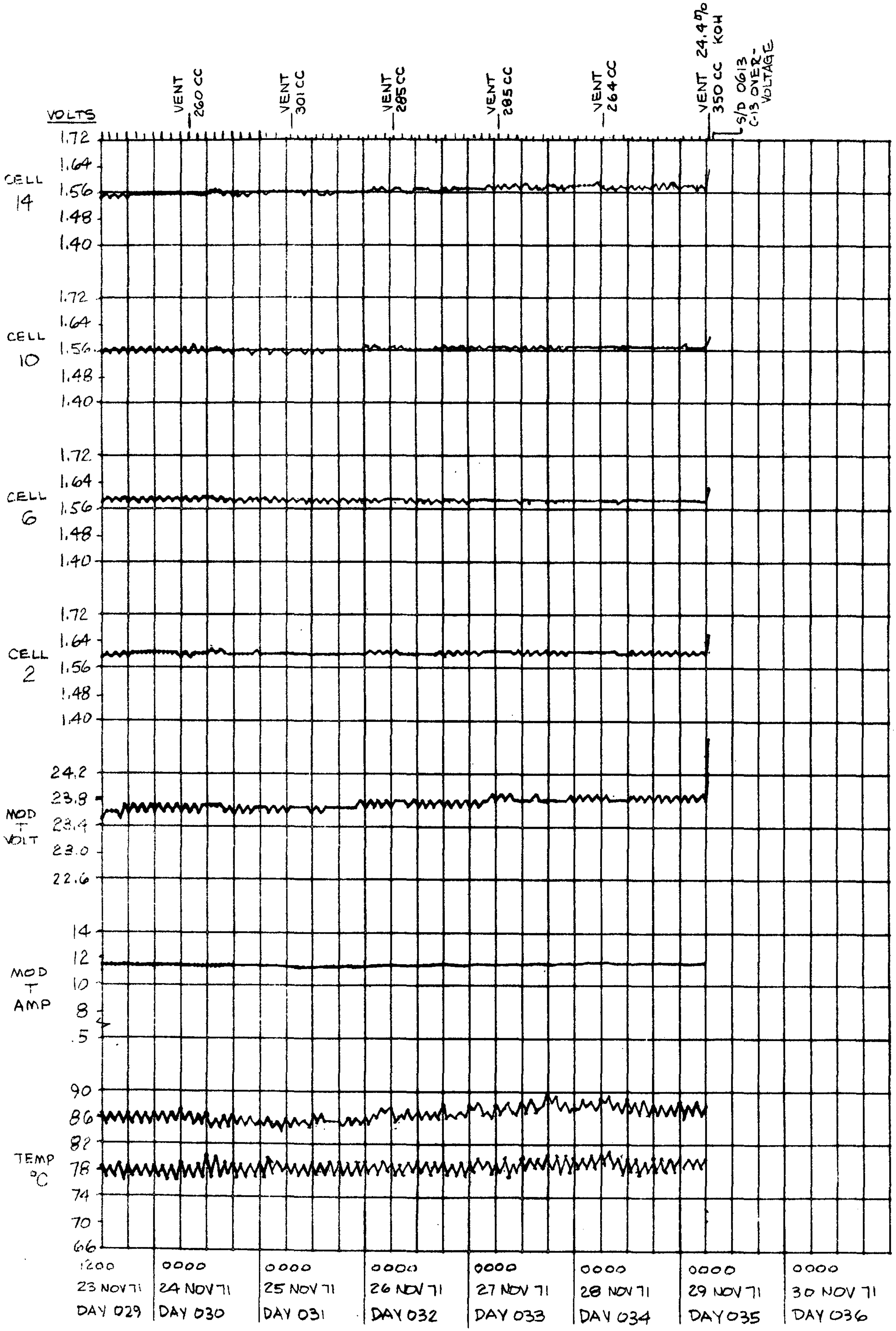


FIGURE 5-156 PERFORMANCE HISTORY (POSITION 3-MODULE 5)



5.7.3 Circulation Effect

In May through September 1971 when the system was being checked out with one module, experience indicated that a circulation condition of 30-seconds duration every half hour was adequate to maintain KOH equilibrium in the module and system and remove any accumulated gas from each cell of the module. When three modules were installed in the system and the feed mode changed from dynamic to static with distilled water entering the module directly, the frequency of circulation was decreased to once every 6 hours. This seemed like a good compromise between LSI test data and past experience. The LSI data indicated that gas buildup would cause module shutdown in approximately 20 hours if electrolyte circulation was eliminated. The 30-second circulation duration was retained.

Operation of the system during the 80-hour checkout test revealed that 6 hours was apparently too long and 30-seconds duration too short. Consequently, the 6-hour period was reduced to one circulation every 2 hours. The 30-seconds duration circulation was increased to 2 minutes because, after flushing a number of modules, a large quantity of KOH was found to be accumulating within them. It was thought that the KOH added to a module after a circulation was not being washed out at the next circulation when only 30 seconds of circulation was employed. Increasing the circulation to 2-minutes duration apparently eliminated the problem as only a small amount of KOH accumulated in each module after the change. The longer circulation did not have any permanent effect on operating levels within the system. Table 5-8 shows the different circulations employed during testing. Figure 5-157 shows the effect that a 2-minute circulation had on the performance of module 5 during the period 1030 to 1100 on 2 November 1971. Thermocouple number 13 is the inlet plumbing line to the module which was heated for 45 minutes preceding circulation.

The 2-minute circulation every 2 hours was retained until 11 January. At that time the conditions were changed to be 2 minutes duration every 6 hours through a given module. This was done because it was thought that the frequent circulations (once every 2 hours) were bringing excess KOH into

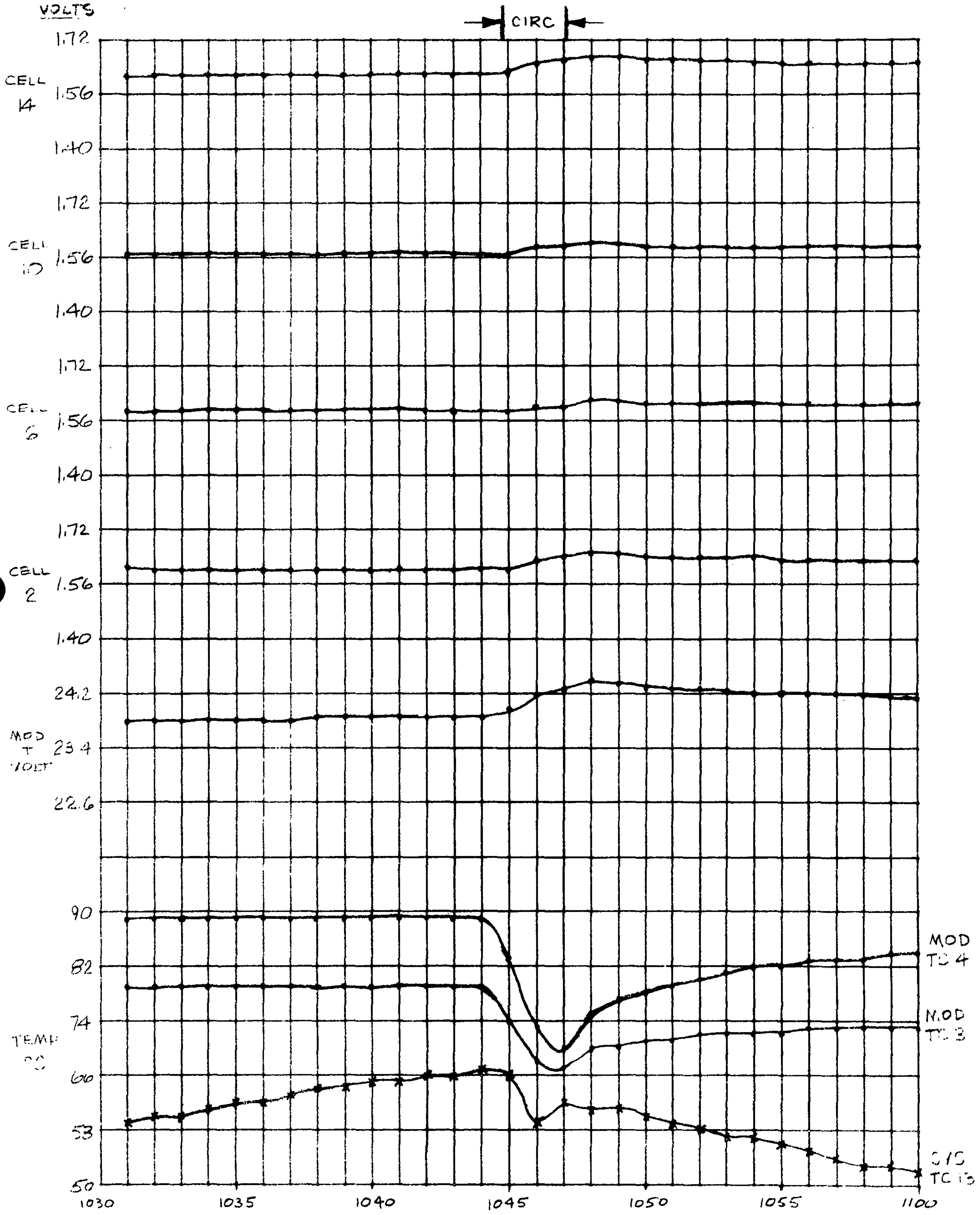
Table 5-8

CIRCULATION CONDITIONS USED

Test Period	Pump Operation Duration	Pump Operation Frequency	Fluid Flow to Modules	Remarks
100-hr c/o test: (1)				
24-28 August	30 sec	30 min	Parallel(3)	1. During 100-hr. checkout test feed water entered circulating loop upstream of separator.
80-hr c/o test: (2)				
12-13 October	30 sec	6 hrs	Parallel	
13-26 October	30 sec	2 hrs	Parallel	2. During all other testing the feed water entered directly into modules after circulating pump stopped. When circulating pump operated, feed water was not supplied to the system.
P/E test: (2)				
27 October - 10 January	2 min	2 hrs	Parallel	
11-19 January	2 min	2 hrs	Sequence(4)	
20-26 January	10 min	2 hrs	Sequence	
26 January - 20 February	Continuous		Parallel	
21 February - 7 April	2 min	2 hrs	Sequence	3. Parallel fluid flow means that circulating fluid passed through all modules simultaneously.
7 - 12 April	2 min	2 hrs	Parallel	
12 - 19 April	30 sec	40 min	Parallel	
19 - 25 April	2 min	6 hrs	Parallel	
				4. Sequence fluid flow means that all circulating fluid passed through only one module during that period of pump operation.

FIGURE 5-157 CIRCULATION EFFECT (POSITION 2-MODULE 5)

1 MIN. SCANS 1030-1100 2 NOV 71 11.3 AMPS



2 NOV71

DAY 008

the module which was not back diffusing out in the two hour period between circulations. KOH still accumulated within the modules and it was decided to increase the circulation duration to 10 minutes. This operation was of limited value because the test was terminated prematurely by a failure of the peripheral equipment. Also, the electrolyte loop concentration was changed at the same time. The limited data collected seemed to show a more stable operation but later it was shown that the KOH accumulation was due to leaking check valves and not limited back diffusion. Thus, the 10-minute circulation test was somewhat meaningless.

The continuous circulation tests between 26 January and 20 February allowed a relatively long period of performance and came close to duplicating the acceptance test operations performed at LSI and A-C. Operation was hindered by leaks and electrolyte concentrations different than specified by the module manufacturer. The first time continuous circulation was used the concentration was relatively low, although the modules did operate about 10 days without problems. On the 10th day both modules were shutdown due to circulating pump failure. The second time continuous circulation was used module 3 developed a large leak that caused the concentration levels to change drastically. Module 2 operated 7 days with unusually low electrolyte concentration before being shutdown manually.

After 21 February, the circulating pump was operated every 2 hours for about 2 minutes to sequence the flow through one module at a time, thus each module was flushed (purged of gas) every 6 hours. Module 2 operated, under these conditions, for 4-1/2 days before failing due to external leaks and high cell voltage. The available data indicates the shutdown was not due to circulation but due to the leakage. Module 3 operated for 11 days. The 2-minute circulation every 6 hours for each module seems to be an acceptable arrangement if the quantity of gas generated within the liquid cavities can be kept low so as not to cause drying of a cell matrix and KOH maldistribution can be controlled. Figures 5-158 through 5-161 show the effect on module performance of a 2.5-minute and a 2-minute circulation. In each case the cells and module returned to the precirculation condition within 20 minutes of the end of the circulation. Figure 5-162 shows the effects of circulation on

FIGURE 5-158 CIRCULATION EFFECT WHEN ADDING 60 GRAMS OF KOH
(POSITION 3- MODULE 3)

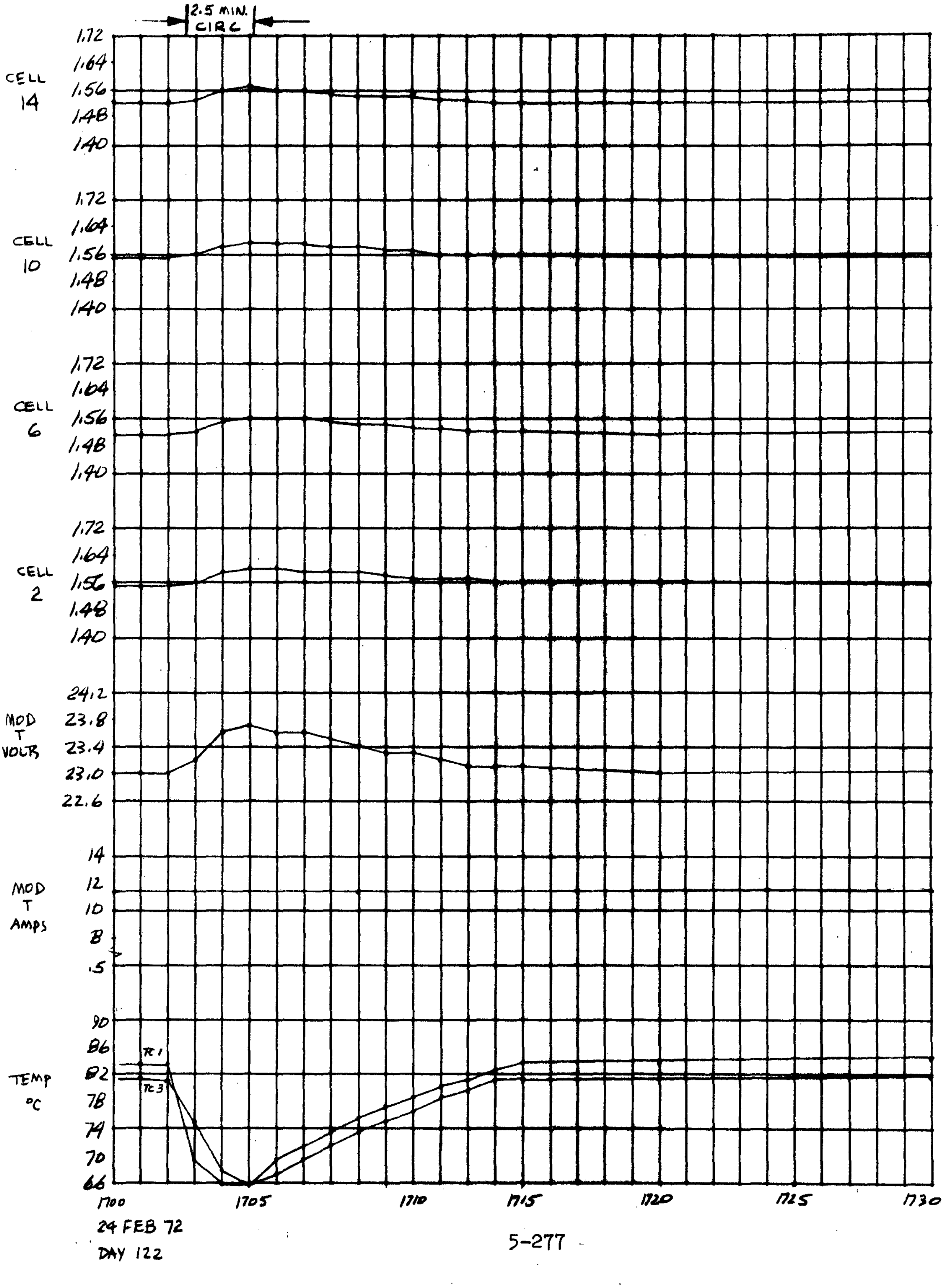


FIGURE 5-159 CIRCULATION EFFECT WHEN ADDING 18 GRAMS OF KOH
(POSITION 3 - MODULE 3)

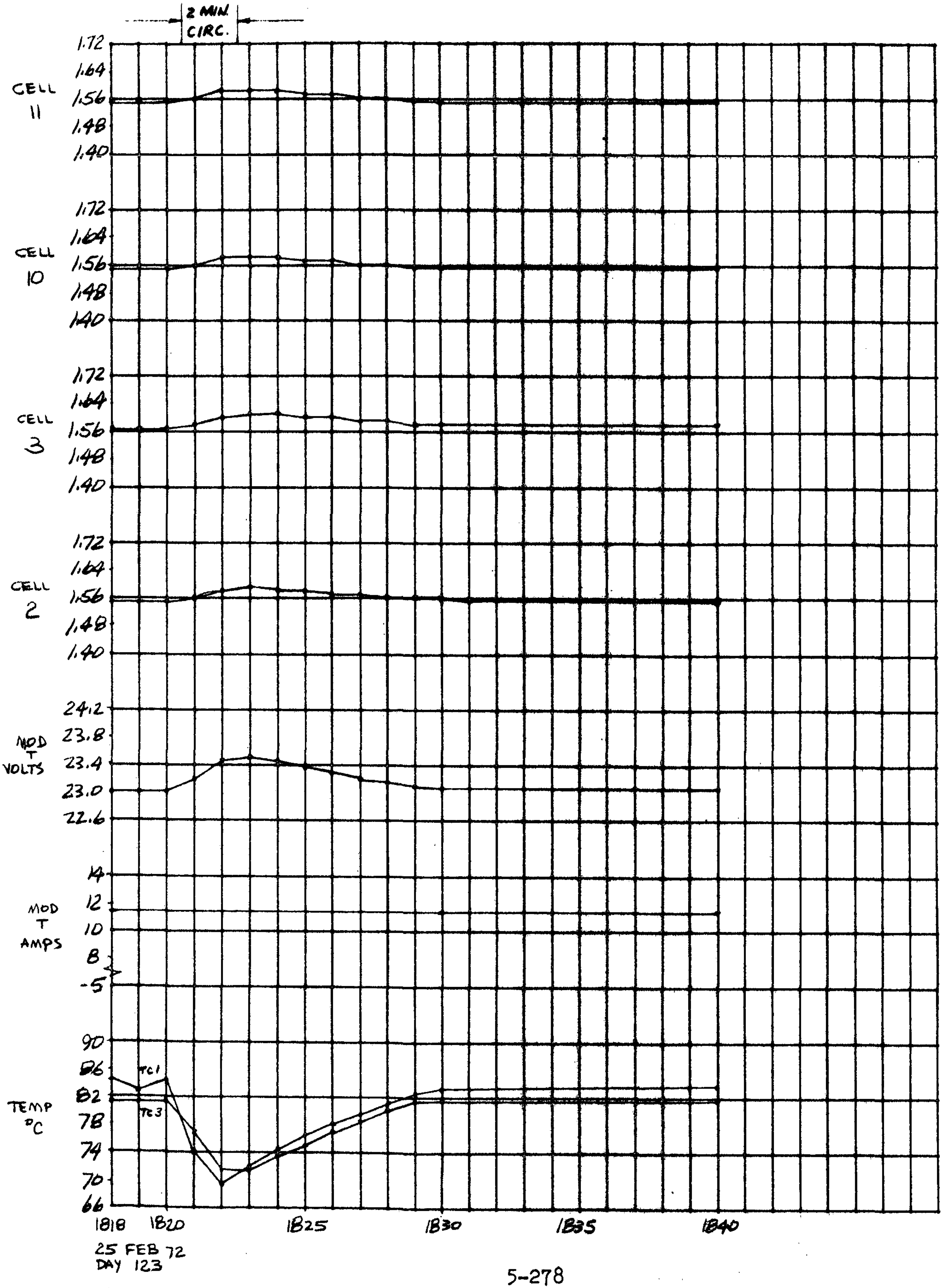


FIGURE 5-160 CIRCULATION EFFECT WHEN ADDING 60 GRAMS OF KOH (POSITION 2 - MODULE 2)

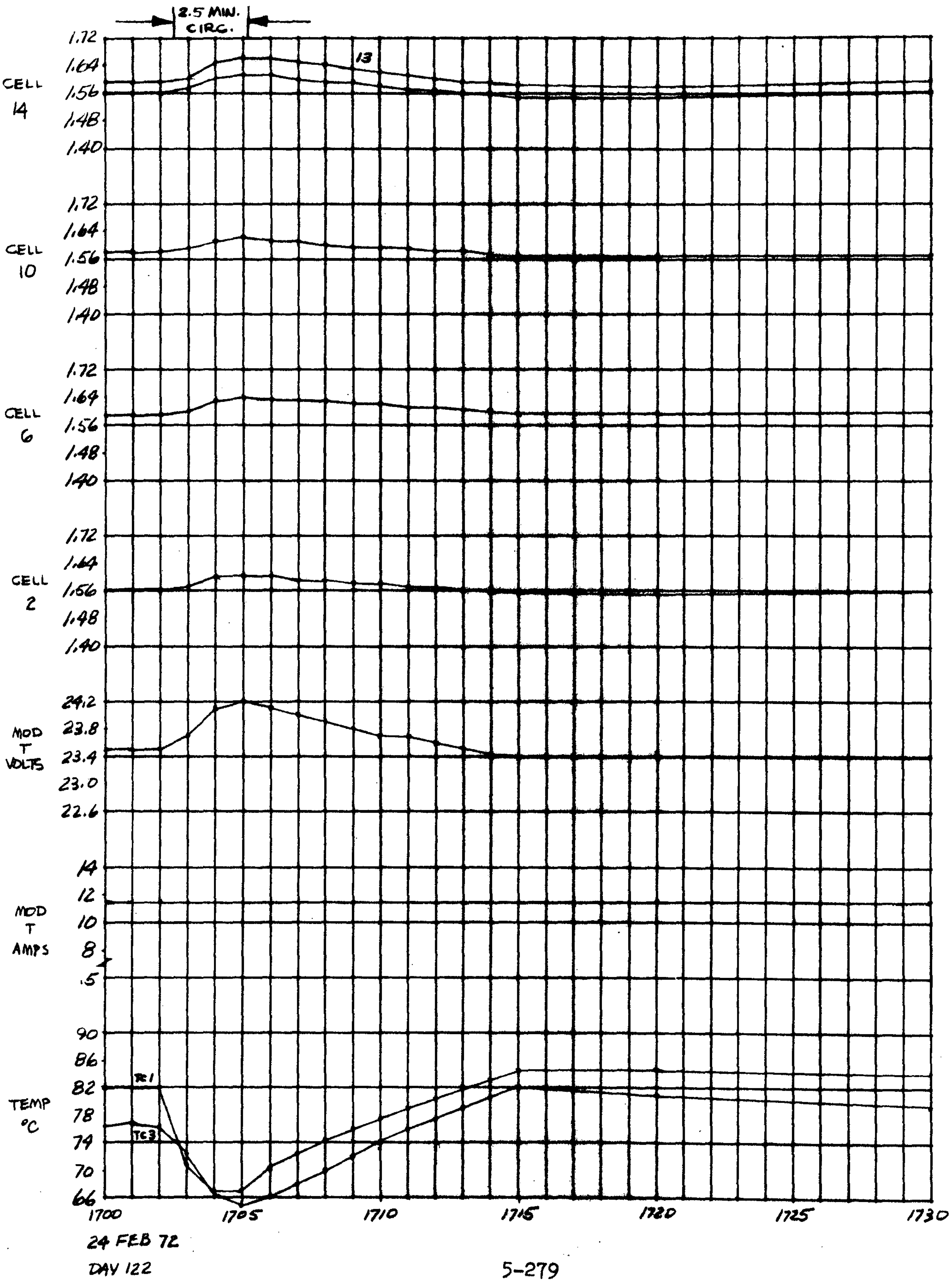


FIGURE 5-161 CIRCULATION EFFECT WHEN ADDING 18 GRAMS OF KOH (POSITION 2 - MODULE 2)

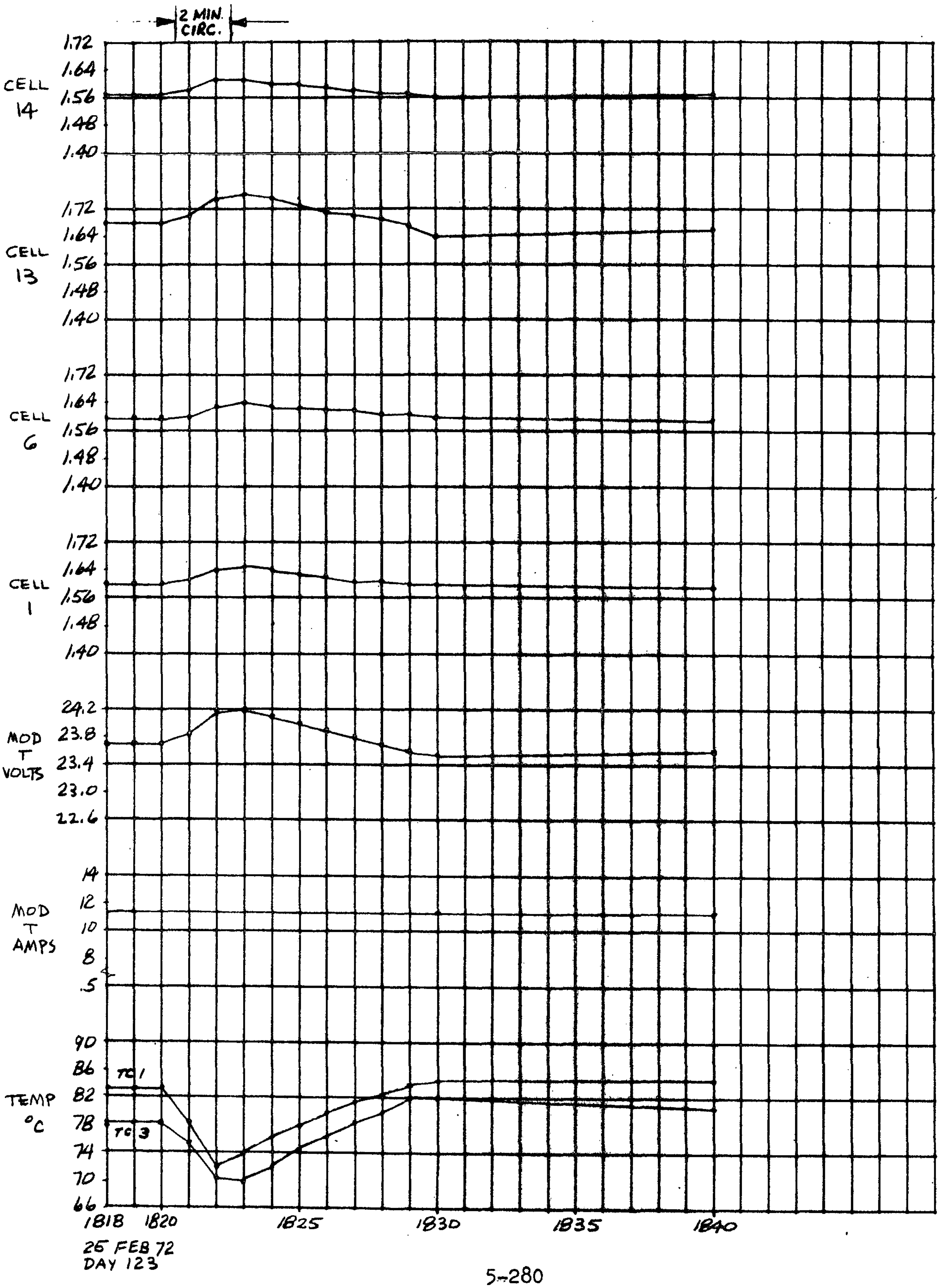
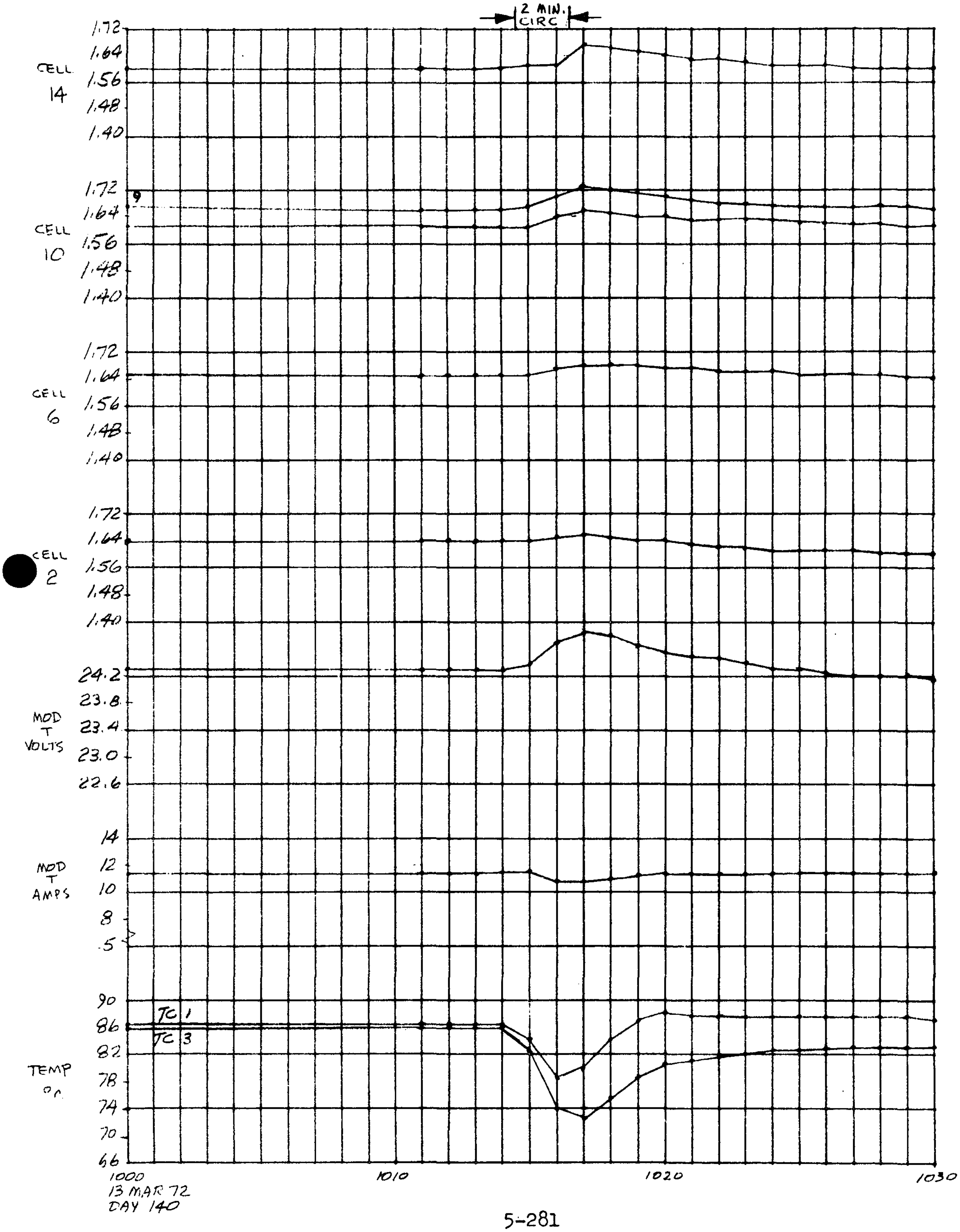


FIGURE 5-162 CIRCULATION EFFECT (POSITION 2- MODULE 2)



the cell and module voltages of module 2 on 13 March. At this time the module had been operating about 5 days with the water feed at the top of the module. The highest voltages and lowest temperatures occur one minute after termination of circulation. The voltages and high temperature return to precirculation conditions within 10 minutes after termination of circulation. The low temperature readout of the module took about 60 minutes to return to precirculation conditions.

The next change was to increase the frequency of circulation to once every 2 hours. This was done because it was found that an electrolyte maldistribution was taking place due to specific gravity difference in cell 15 of the two fluids--electrolyte and distilled feed water. Analysis suggested more frequent circulation of loop electrolyte to reduce the duration for back diffusion of KOH. This change did not seem to help. Next the circulation configuration was changed to 30 seconds every 40 minutes. This was an attempt to duplicate the pretest checkout configuration. The conditions were not quite the same because during pretesting the makeup water entered the system upstream of the separator thus the modules never experienced a direct feed of distilled water. During endurance testing the water feed entered directly into the module after about 15 minutes of operation, thus the KOH washout effect in cell 15 was still possible and was experienced. The final configuration was 2-minutes circulation every 6 hours with all the flow passing through all modules simultaneously. This configuration was employed to try to minimize the thermal changes within the system. By flowing through all the modules simultaneously, more heated electrolyte was flowing thus a higher average temperature and less thermal shock to the electrodes and more rapid return to normal temperatures after pumping stops. This configuration did not seem to produce any improvement in performance.

5.7.4 Concentration Effects

Electrolyte concentrations and distributions within the cells, modules and circulation loop were shown to be a problem in the 90-day manned test of the SVFU. As a result, some pretest analysis was conducted to determine the distribution that could be expected during the 182-day test if static feed of electrolyte was employed. Other problems were experienced during actual testing. The following subparagraphs describe the analysis conducted and the problems experienced during this test program.

5.7.4.1 Pretest Analysis

Normally the manufacturer of the SVFU, Allis-Chalmers, tested the modules at their facility with all cell cavities and the system charged with 35% KOH solution and with continuous electrolyte circulation. Then, when they delivered a system, the operating instructions would stipulate that the circulating pump was to operate approximately 3 minutes every 2 hours. Continuous circulation was sufficient to maintain uniform concentration within the system without KOH buildup in the matrices. Distilled water was added to the moving fluid and was thoroughly mixed at the same rate it was being consumed in the modules. When the circulating loop concentration was constant, which it was under these conditions, a predictable change in electrolyte matrix volume was possible and the system worked within a constant and uniform range. According to the experimental data obtained from Allis-Chalmers Company, a vapor pressure differential driving force of approximately 4.82×10^3 N/m^2 differential (0.7 psid) was required between the water matrix and the electrolyte matrix to allow water vapor diffusion. Although a number of variables affect this value; using it produces acceptable results for analysis when the system is operating at 353°K (176°F), 20.6×10^4 N/m^3 gage (30 psig) and 11.3 amperes per module.

Figure 5-163 shows the vapor pressure of caustic potash solutions versus the electrolyte concentrations within the system. Assuming the conditions stated above; that is, an initial charge of 35% KOH, continuous electrolyte circulation and 353°K (176°F) operating temperature, the electrolyte matrix concentration would have to change from 35% to 40% in order to establish the proper vapor pressure differential driving force. Figure 5-164 shows that the volumetric change to the quantity of liquid in the electrolyte matrix was about 16.5%. This was determined by starting at the left edge of the curve and moving upward and to the right between the two lines (34 and 36%) until the 35% line crosses the 40% horizontal line, then read the volumetric change on the

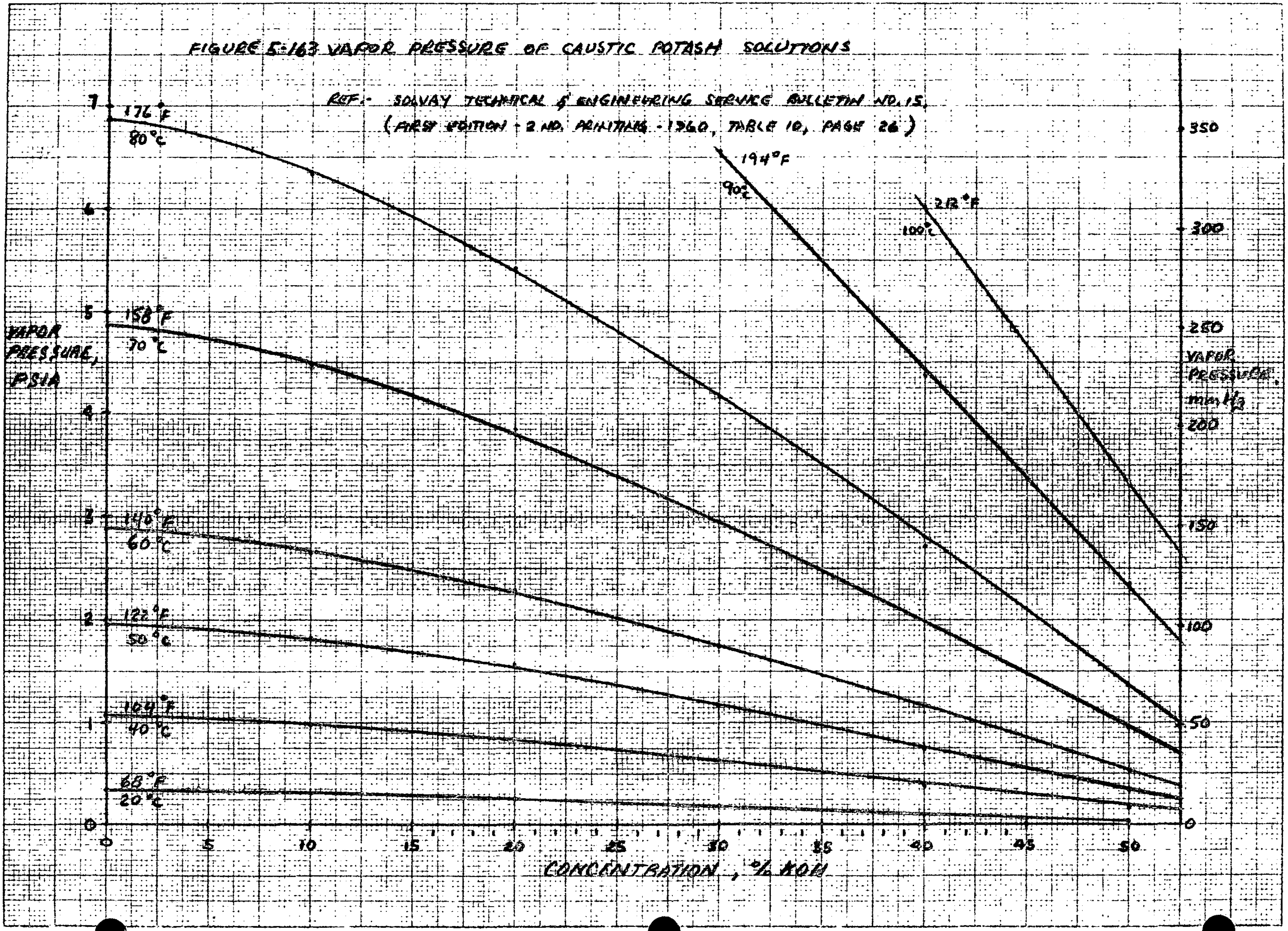


FIGURE 5-163 VAPOR PRESSURE OF CAUSTIC POTASH SOLUTIONS

REF.- SOLVAY TECHNICAL & ENGINEERING SERVICE BULLETIN NO. 15.
(FIRST EDITION - 2 ND. PRINTING - 1960, TABLE 10, PAGE 26)

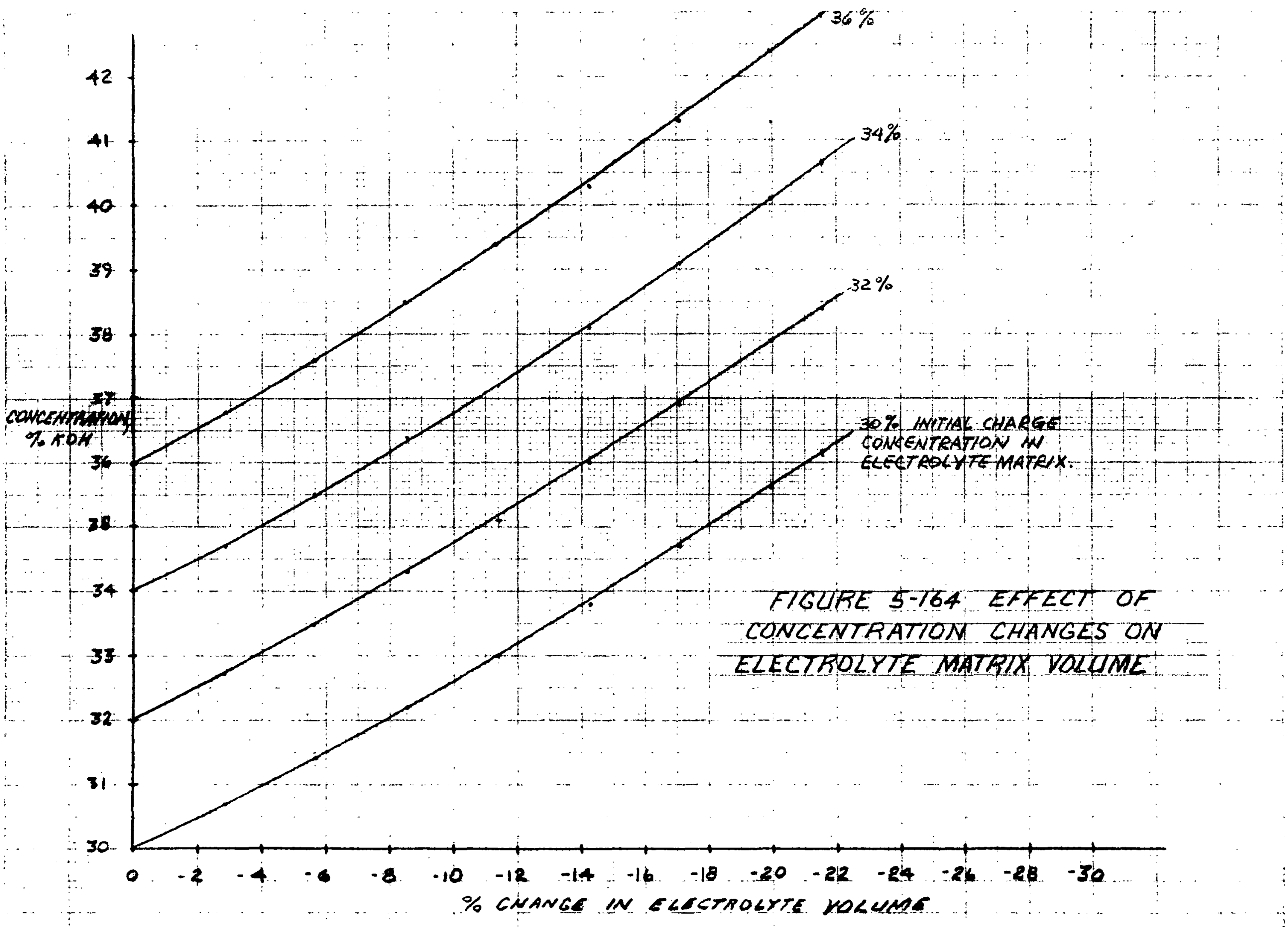


FIGURE 5-164 EFFECT OF CONCENTRATION CHANGES ON ELECTROLYTE MATRIX VOLUME

10-11-71 GJ

abscissa. This change in volume is acceptable and would be constant for all cells in a module with continuous circulation.

When the water feed mode is changed, as is the case when the circulation pump is operated for short durations at uniform frequencies, an adjustment is required in the initial charge concentration conditions of the modules and the electrolyte loop. A number of short-term tests and a 100-hour checkout test of the system was performed at MDAC using this concept. Over a 4-month period of time, the system was operated with gradually decreasing initial charge concentration until it was found by experimentation that operating the electrolyte circulation pump for 30 seconds every 30 minutes and charging the system with 31.0% KOH solution resulted in good and uniform performance. Calculations were made to better understand the results obtained during testing. Three curves were set up similar to Figure 5-165. This curve shows the conditions for 30% initial charge concentration and the changes that take place as the water matrix concentration increases while water and KOH enter the cell. The other curves represented initial charge concentrations of 25 and 35%. All curves considered matrix porosity of 30, 60 and 90% and two conditions, zero and maximum, of back diffusion of KOH from the water matrix into the water cavity. A study of diffusion phenomena indicated that the back diffusion rates should be close to maximum. Porosity measurements indicated that the porosity of the asbestos material used in the matrices was about 60%. As a result, Figure 5-166 was developed using 60% porosity and maximum diffusion for all three initial charge values. This curve indicates that at an initial charge of 31% and circulation at 30-minute intervals, the maximum concentration reached in any cell would be 35.7 to 36.0%. This results in an electrolyte matrix volumetric change of about 17.0 to 17.5%. Long-term testing, i.e., periods in excess of 100-hours, were not performed; consequently, it is not possible to state whether or not the configuration just described would be adequate for long-term operation.

Testing during the 182-day test was to be performed with intermittent electrolyte circulation. In this case, distilled water was to enter the module a short time after the circulation pump stopped. The plumbing config-

FIGURE 5-165
KOH CONCENTRATION WITH
30% INITIAL CHARGE

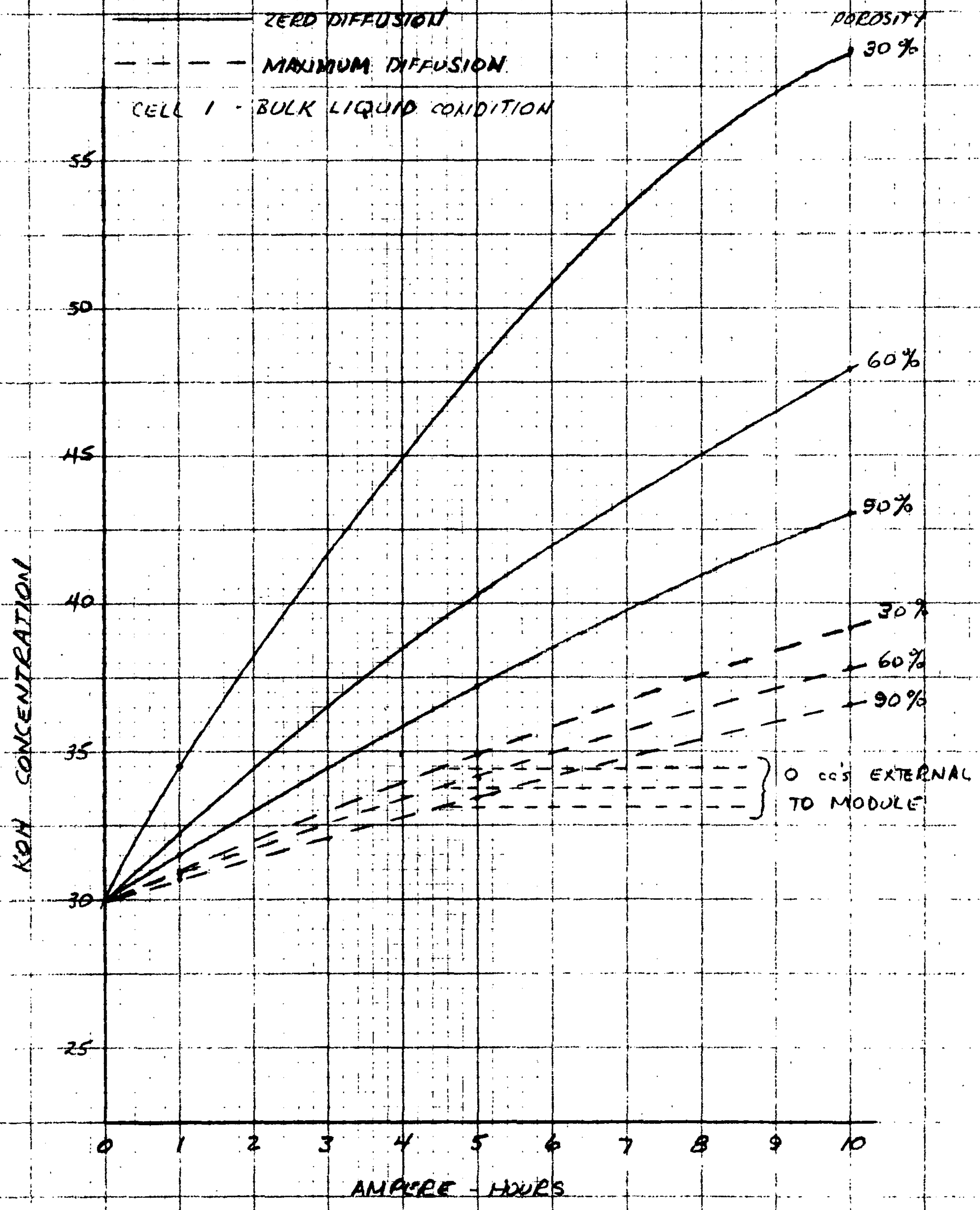
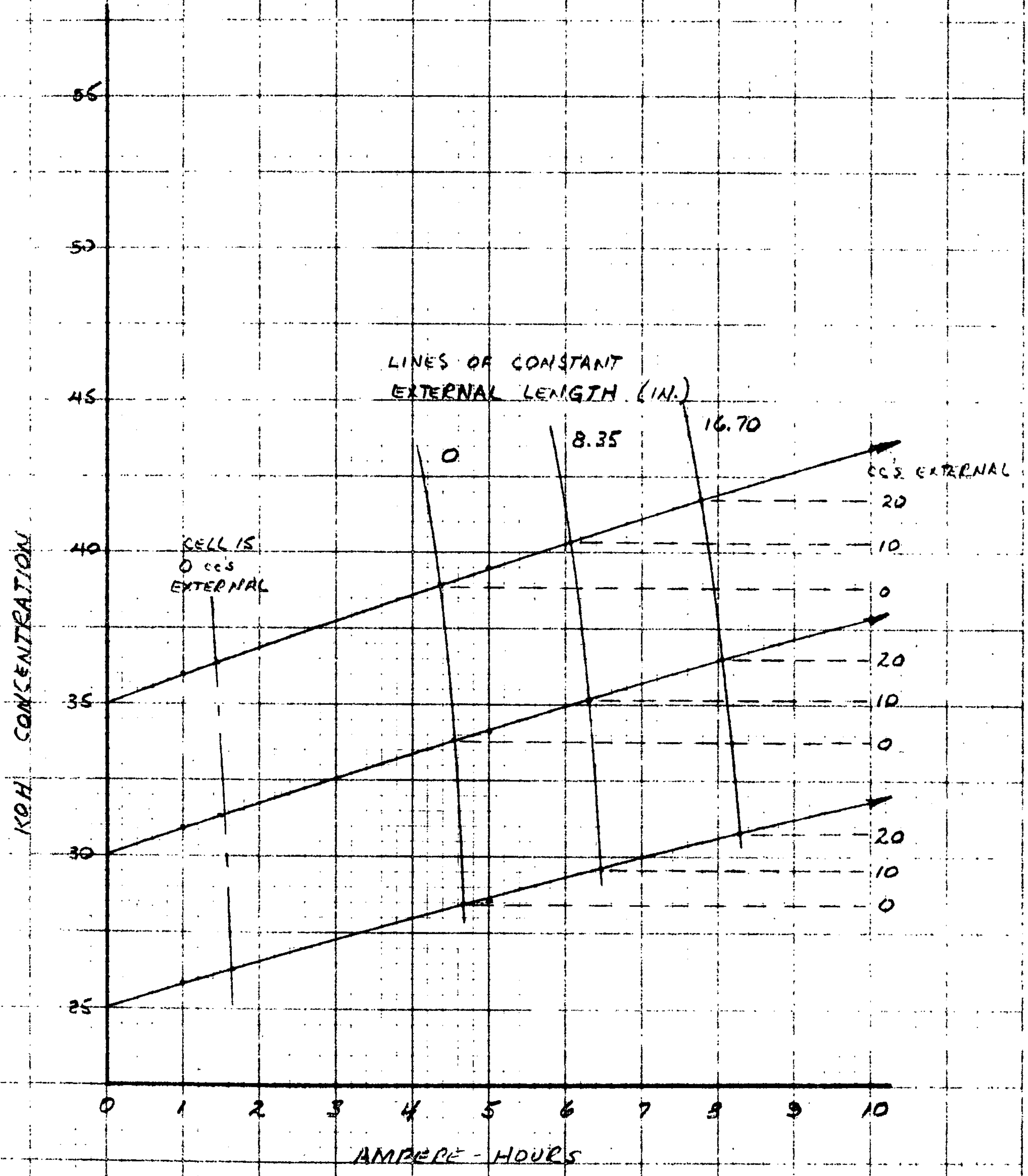


FIGURE 5-166

KOH CONCENTRATION AT
60% POROSITY CONDITION
WITH MAXIMUM DIFFUSION

0.25 IN. I.D. ALL TUBES & FITTINGS

CELL NO. 1 CONDITIONS



uration to be used is shown in Figure 5-167. The total length of plumbing, external to the module, between the module entrance and the branch of the tee admitting distilled water is less than 9 cc; as a result, the concentration within the water cavity and matrix will gradually rise until distilled water enters the cells. This is shown on Figure 5-166 for 0, 10 and 20 cc's external to the module. The volume of plumbing external to the module was to be kept as small as practicable to minimize the variation in electrolyte concentration before distilled water entered the module. The distance between the distilled water supply tee and the different cells in the module varied. Cell 1, the furthest from the tee, would receive more KOH than cell 15 (see Figure 5-167). The difference in concentration between these two cells, assuming zero external plumbing, is about 5%. Using this information and an initial charge of 31%, it is possible to determine the actual volumetric change to be expected in the electrolyte matrix of the two extreme cells, 1 and 15, for the specific configuration of the 182-day test as follows:

	initial charge all matrices	water matrix when H_2O enters	electrolyte matrix final concentration	electrolyte matrix volumetric change
Cell 1	31%	36.5%	41.5%	32.5%
Cell 15	31%	34.0%	39.2%	27.0%

These values were not considered undesirable and testing was started with an initial charge concentration of 32%. Performance during the 182-day test will be described in Section 5.7.4.2.

All the analysis and calculations performed for this Section were accomplished under the sponsorship of the McDonnell Douglas Astronautics Company in-house capital funding and independent research and development funding.

5.7.4.2 Electrolyte Maldistribution

Electrolyte maldistribution was probably the most significant problem encountered in testing the SVFU and the most significant cause of continuous operations being limited to about 6 to 10 days. In the initial configuration

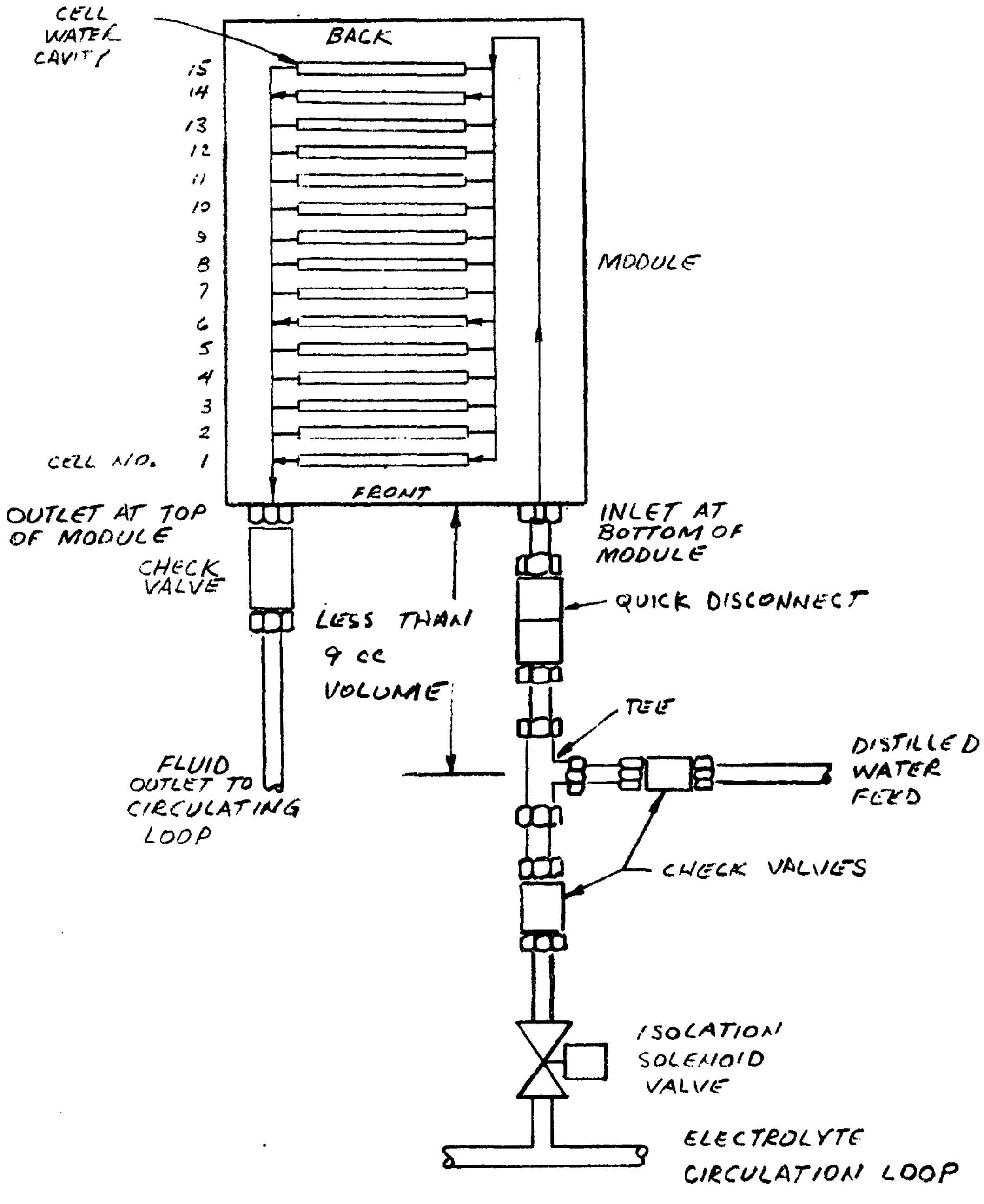
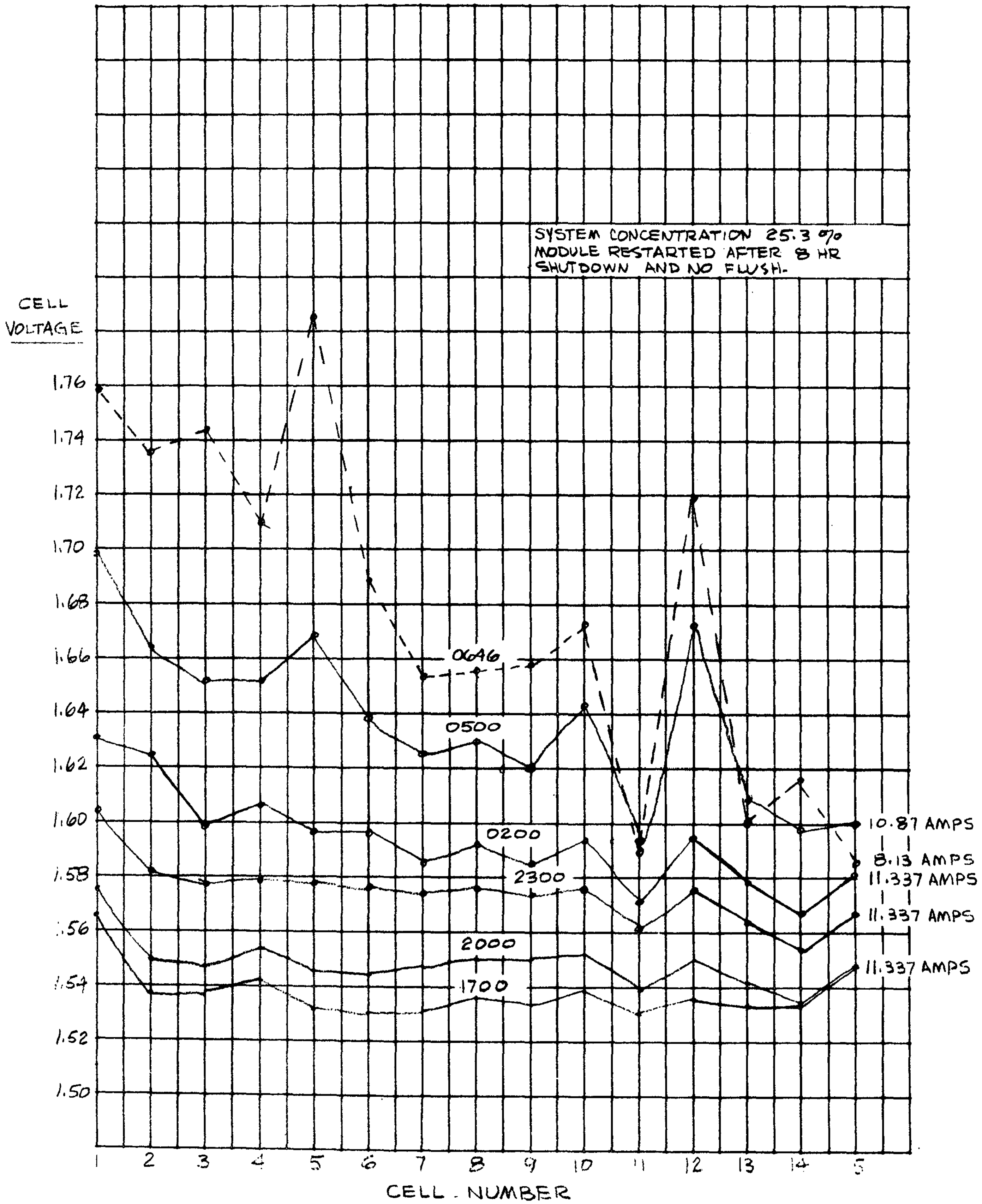


FIGURE 5-167 -

STATIC FEED PLUMBING CONFIGURATION AND WATER DISTRIBUTION WITHIN MODULE of module plumbing, check valves were installed in the electrolyte loop, upstream of the inlet to the modules (reference Figure 5-167). This proved unsatisfactory as the check valves were not all identical and cross-feeding of electrolyte between modules, on the discharge side, began to affect performance. The plumbing was modified to place the check valves at the electrolyte outlet to the module to prevent the back feeding (see Figure 5-167). Also, the isolation solenoid valves at the module inlet were rewired to be closed at all times except when the circulation pump was operating. This improved performance but not enough to gain long-term operation. Simultaneous with the plumbing change, some improvement was also obtained by reducing the initial concentration from 32.0% to 30.0 ± 0.5%, and the circulation sequence was changed to 30 seconds every 2 hours instead of 30 seconds every 6 hours. Performance was further complicated by the observation that the H_2 cavities of the modules were collecting KOH. The flushing procedure was modified to require flushing all 3 cavities instead of only the H_2O and O_2 cavities. The next change was to reduce the concentration in the electrolyte loop from 30.0% to 26 ± 1% KOH. Some more improvement was obtained in module operation. However, KOH buildup was still evident in the modules and it was decided to change the circulation duration from 30 seconds to 2 minutes. It was thought that the 30-second period was insufficient to return the matrix concentration to its original level. A series of curves were prepared, see Figures 5-168 through 5-170 which show the performance of each cell in module 3, at essentially constant current and varying system electrolyte concentrations. All figures are identical, except the circulation conditions shown in Figure 5-168 which were for 30-seconds duration and the others were 2 minutes. All the curves show that front cells had higher voltages than back cells (see Figure 5-167). The data indicates that the cells were collecting KOH and that the front cells would collect more as they were further from the source of distilled water and closer to the source of KOH due to back feeding. Figure 5-170 shows lower cell voltage because the loop concentration was lower and, therefore, it would take longer for the KOH to buildup in the cells. Also, some flooding may have occurred because the cells had just been flushed with a 30.0 ± 0.5% KOH solution prior to being installed in the system. That would also have a tendency to keep cell voltages down.

FIGURE 5-168 PERFORMANCE PROFILE (POSITION 2-MODULE 3)

CIRC 30 SEC EVERY 2 HRS @ 1840, 2040, 2240, ETC., 22/23 OCT 71



SYSTEM CONCENTRATION 25.3 %
MODULE RESTARTED AFTER 8 HR
SHUTDOWN AND NO FLUSH.

FIGURE 5-169 PERFORMANCE PROFILE (POSITION 2-MODULE 3)

CIRC 2 MIN. EVERY 2 HRS @ 1445, 1645, 1845, ETC., 27/28 OCT 71

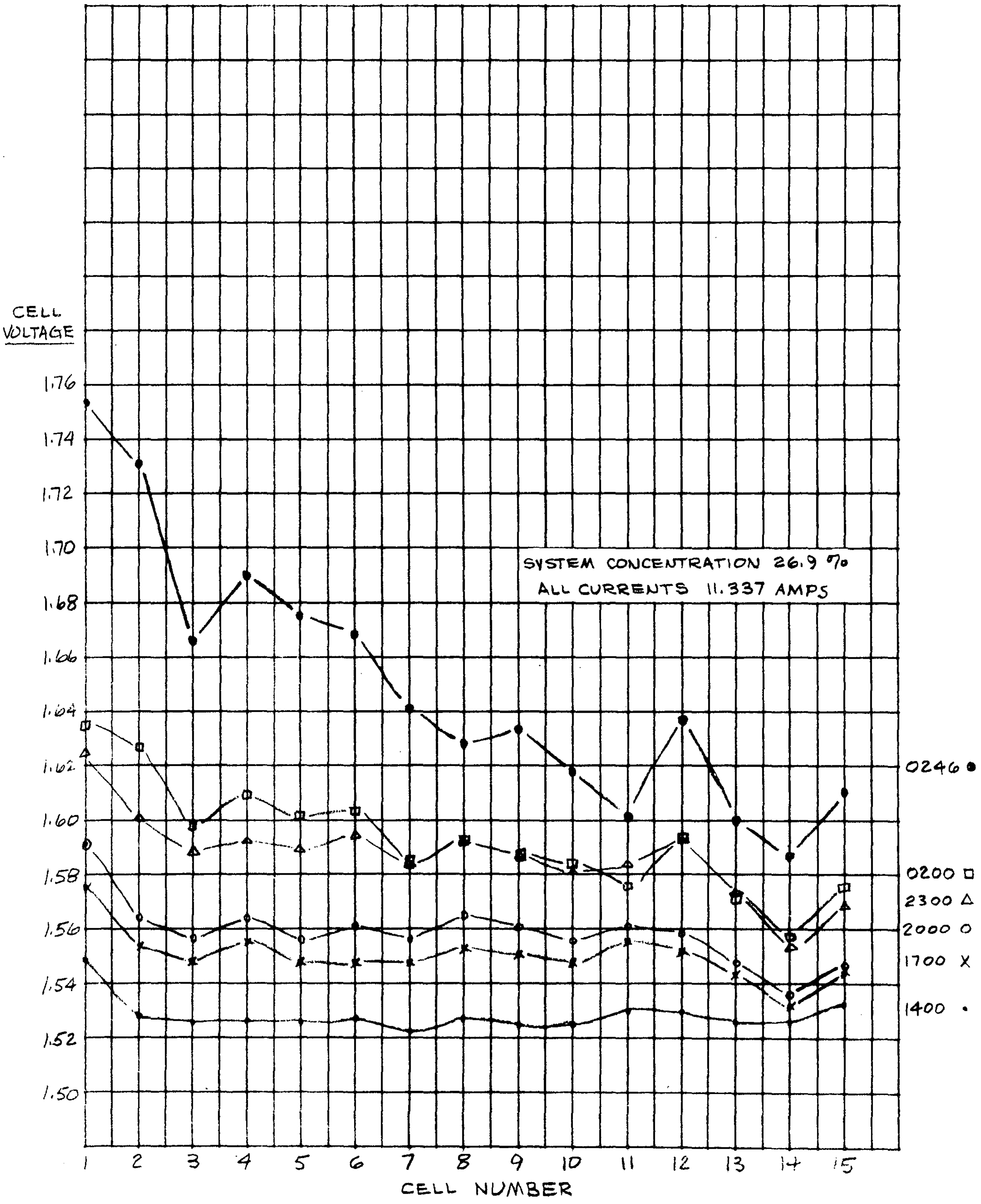
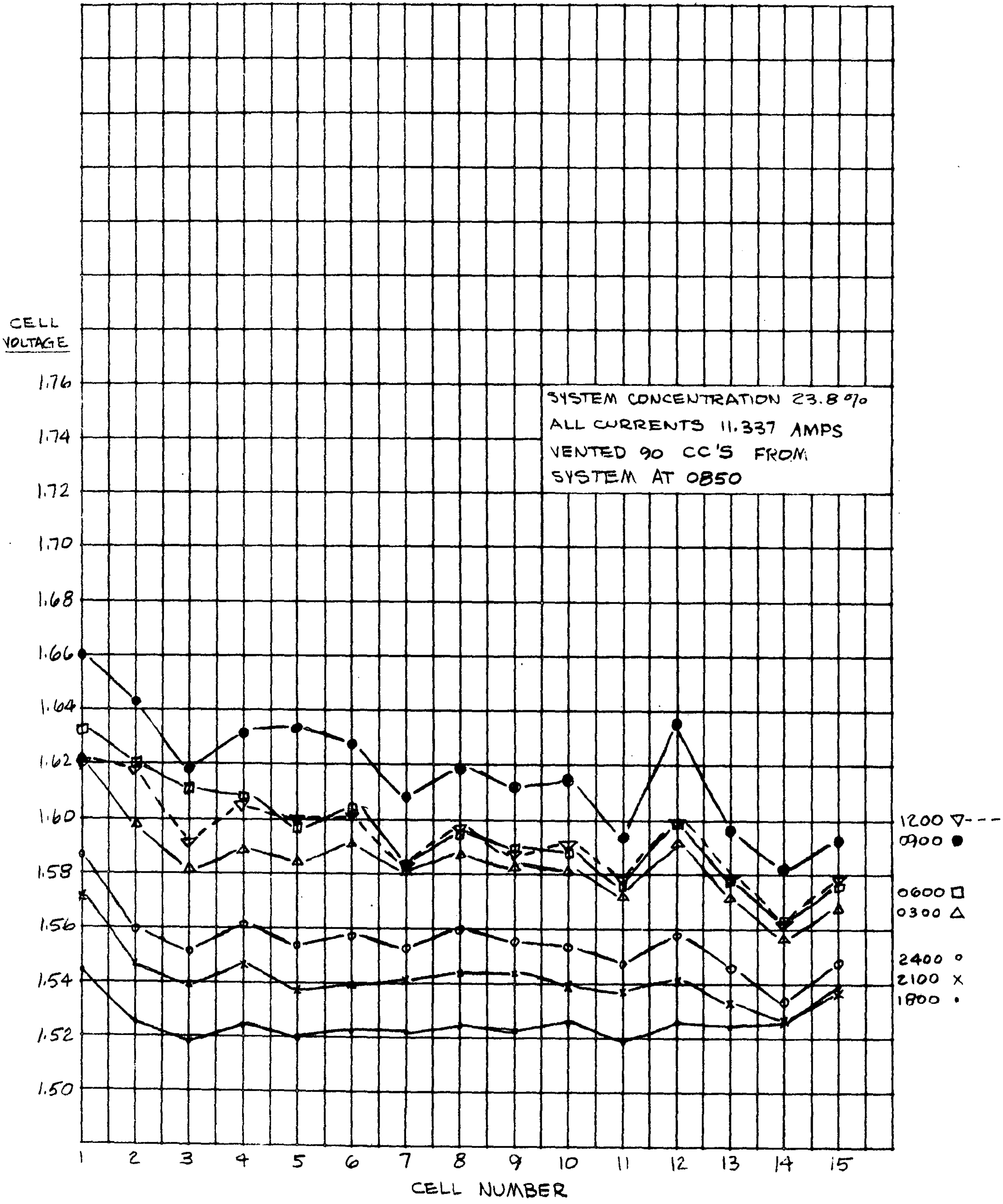


FIGURE 5-170 PERFORMANCE PROFILE (POSITION 3- MODULE 3)

CIRC 2 MIN. EVERY 2 HRS @ 1845, 2045, 2245, ETC., 28/29 OCT 71

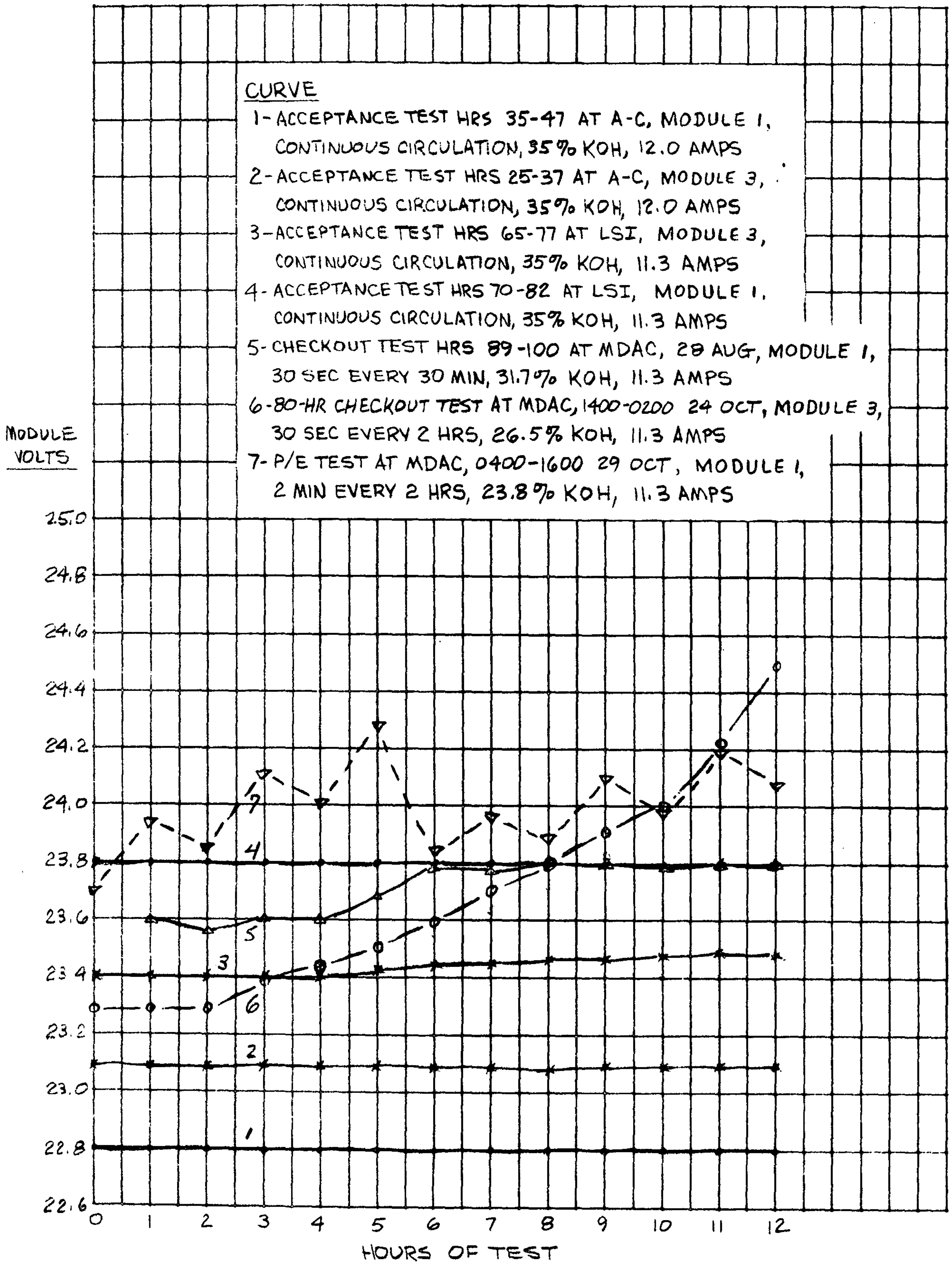


Another series of curves were prepared to compare the performance of the modules at various test facilities. Figures 5-171 through 5-173 present this information. Figure 5-171 indicates that module 3 performed better with both a 2-minutes circulation each 2 hours and lower concentration. It is impossible to account for the difference in performance between the A-C and LSI facilities. Figure 5-172 shows the performance of module 4 and Figure 5-173 shows module 5 performance. In both cases it is evident that these new modules are less susceptible to concentration changes than the old modules due to the fact that a salt bridge probably existed in the cells. Module 4, curve 5, shows slightly higher module voltage at the end of the 12-hour period because the module was only 5 hours from failure due to over-voltage on cells 13 and 15 due to external leaks between these cells.

Numerous startups were accomplished all with matrices charged at 30.0 ± 0.5% KOH and the loop charged at 26.0 ± 0.5%. In all cases the concentration in the loop dropped and the modules exhibited symptoms of KOH accumulation. The startup on 20 January used a loop concentration of 23.0% KOH. The matrices were retained at 30.0 to 30.5% KOH. This configuration showed stable operation for about 2-1/2 days for modules 2 and 3 when the 115 volt AC circuit failure caused system shutdown. Whether the concentration change or the circulation change caused the stable performance is not known. The startup on 26 January used continuous circulation with loop and matrices at 30.2% KOH. This condition showed fairly stable operation at 8 amperes. Increasing the current caused increased and unstable cell voltages. Concentration readings were taken daily and showed that the electrolyte loop initially dropped to 27.9% KOH and then gradually increased to 28.7% KOH. The increase was partially caused by adding 15 to 20 cc's of 30.2% KOH to the loop each day that an electrolyte sample was taken. This operation implied very little KOH accumulation in the matrices when continuous circulation is used. However, this condition of operation was inadequate for high current levels as the cell voltages were much higher than they should have been. Leakage also hindered evaluation as the concentration continued to fall slowly even though some KOH was added each day that a KOH sample was withdrawn from the system.

FIGURE 5-171 COMPARISON OF PERFORMANCE

(MODULES 1 & 3 AT VARIOUS TEST FACILITIES)



CURVE

1- ACCEPTANCE TEST HRS 35-47 AT A-C, MODULE 1, CONTINUOUS CIRCULATION, 35% KOH, 12.0 AMPS

2- ACCEPTANCE TEST HRS 25-37 AT A-C, MODULE 3, CONTINUOUS CIRCULATION, 35% KOH, 12.0 AMPS

3- ACCEPTANCE TEST HRS 65-77 AT LSI, MODULE 3, CONTINUOUS CIRCULATION, 35% KOH, 11.3 AMPS

4- ACCEPTANCE TEST HRS 70-82 AT LSI, MODULE 1, CONTINUOUS CIRCULATION, 35% KOH, 11.3 AMPS

5- CHECKOUT TEST HRS 89-100 AT MDAC, 28 AUG, MODULE 1, 30 SEC EVERY 30 MIN, 31.7% KOH, 11.3 AMPS

6- 80-HR CHECKOUT TEST AT MDAC, 1400-0200 24 OCT, MODULE 3, 30 SEC EVERY 2 HRS, 26.5% KOH, 11.3 AMPS

7- P/E TEST AT MDAC, 0400-1600 29 OCT, MODULE 1, 2 MIN EVERY 2 HRS, 23.8% KOH, 11.3 AMPS

FIGURE 5-172 COMPARISON OF PERFORMANCE (MODULE 4)

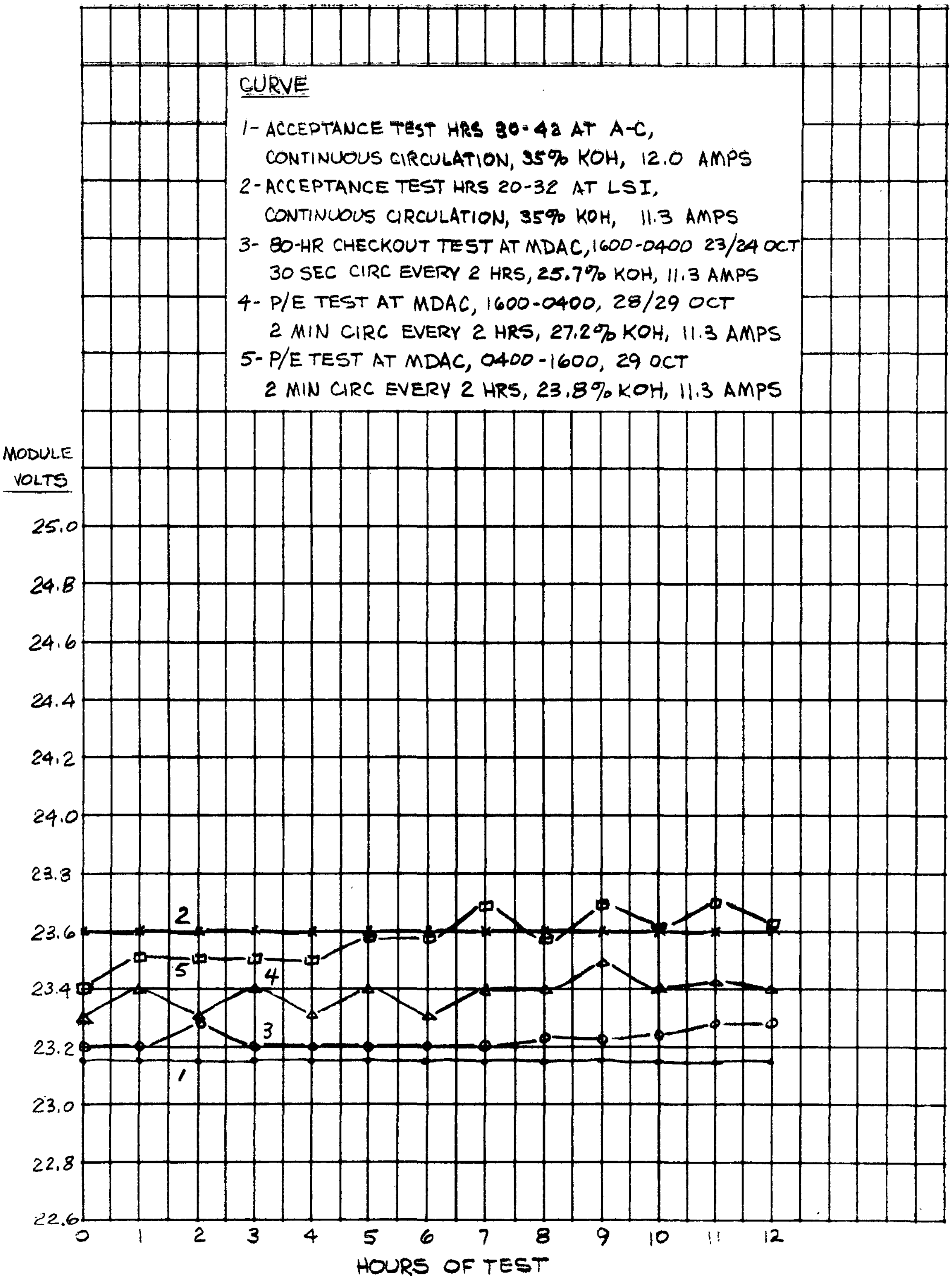
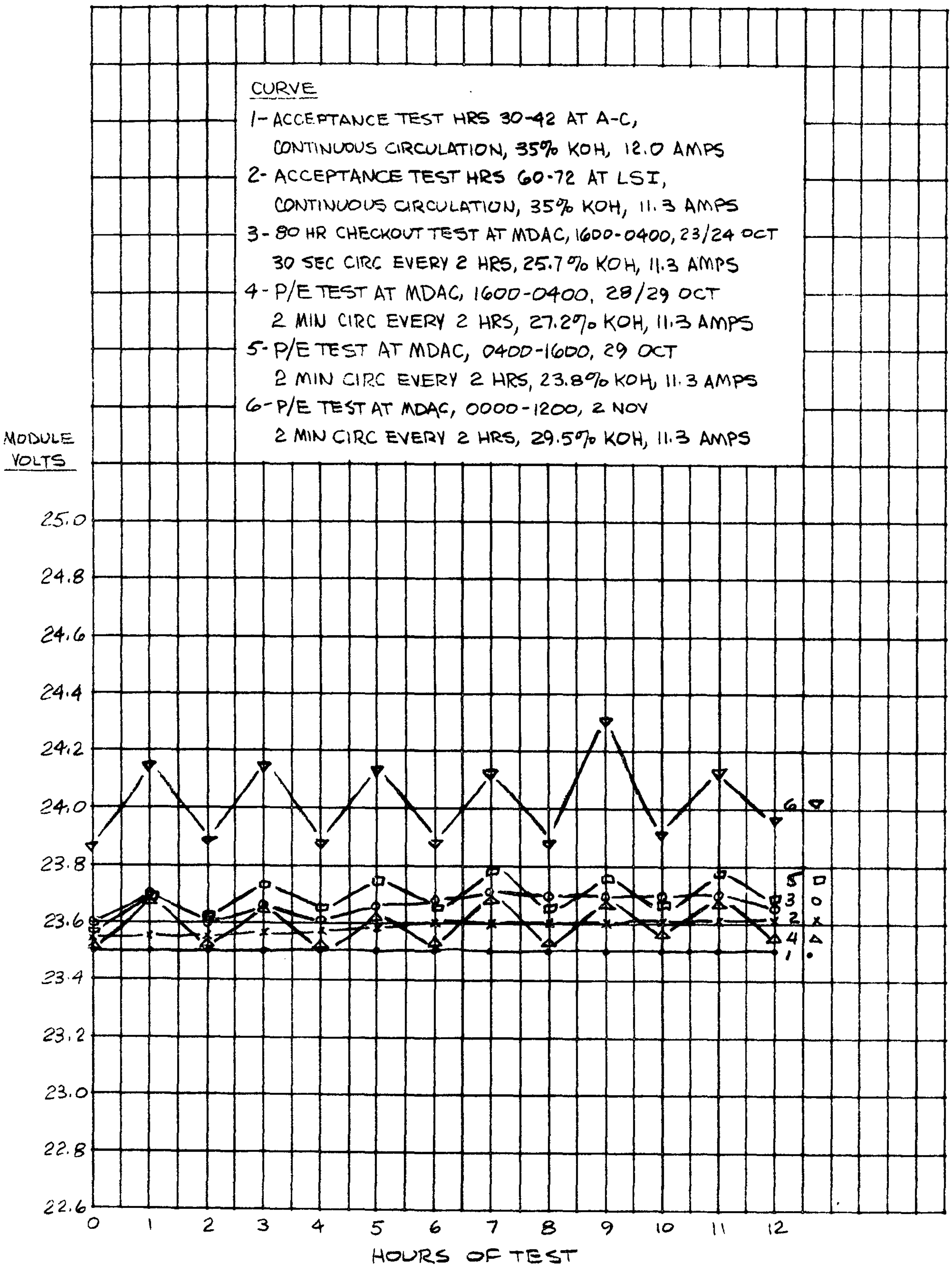


FIGURE 5-173 COMPARISON OF PERFORMANCE (MODULE 5)



The next concentration condition used 35% KOH in all module cavities and the electrolyte loop. This was the condition recommended by the manufacturer. This condition allowed operation at 11.3 amperes but continuous operation was hindered by a massive leak in module 3 that dropped the loop concentration from 35% to about 18% KOH in 24 hours. Module 3 was removed from the system and module 2 continued to operate with this adverse low concentration for about another 4 days. It is difficult to say how the performance would have been if the leak had not developed.

The concentration condition started on 21 February employed 30.0 to 30.5% in the matrices and 25.8% KOH in the electrolyte loop. Also at this time solenoid valves were used to replace the leaky check valves at the module outlets. Under these conditions the modules were able to operate at 11.3 amperes but again the analysis was hindered by a leak in module 2. This time, however, KOH was added to the electrolyte loop as soon as it was possible to determine the approximate amount lost. Thus, it was possible to keep the concentration above 22% as a low value and generally above 24% as a mean value. The leak in module 2 allowed 115 grams of KOH to be lost from the system. Of this amount 78 grams were added back in during the period that two modules were operating. The concentration was raised to 25.2% KOH both times the adjustments were made. The addition of the KOH did not seem to have any detrimental effect on the cells or modules. When only module 3 was operating, the concentration within the electrolyte loop remained fairly constant, thus implying that under these conditions of operation the matrices were not accumulating excess KOH.

Although the cell matrices did not exhibit any significant KOH accumulation, a maldistribution of electrolyte was taking place that apparently was masked earlier by the leaking check valves. This is evident by reviewing Figures 5-174 and 5-175 which show the cell voltages for each cell in the module at the midnight reading for the indicated date. Cells 1 through 13 have relatively constant cell voltages for the 4 to 6 days plotted. Cells 14 and 15 have cell voltages that increase each day. The increase for cell 15 was greater than the increase for cell 14 for the same period of time. Ordinarily, the distilled feed water enters the bottom of the module and follows a mani-

FIGURE 5-174 CELL VOLTAGE PROFILE

0000 READINGS ON INDICATED DAYS 11.3 AMPS

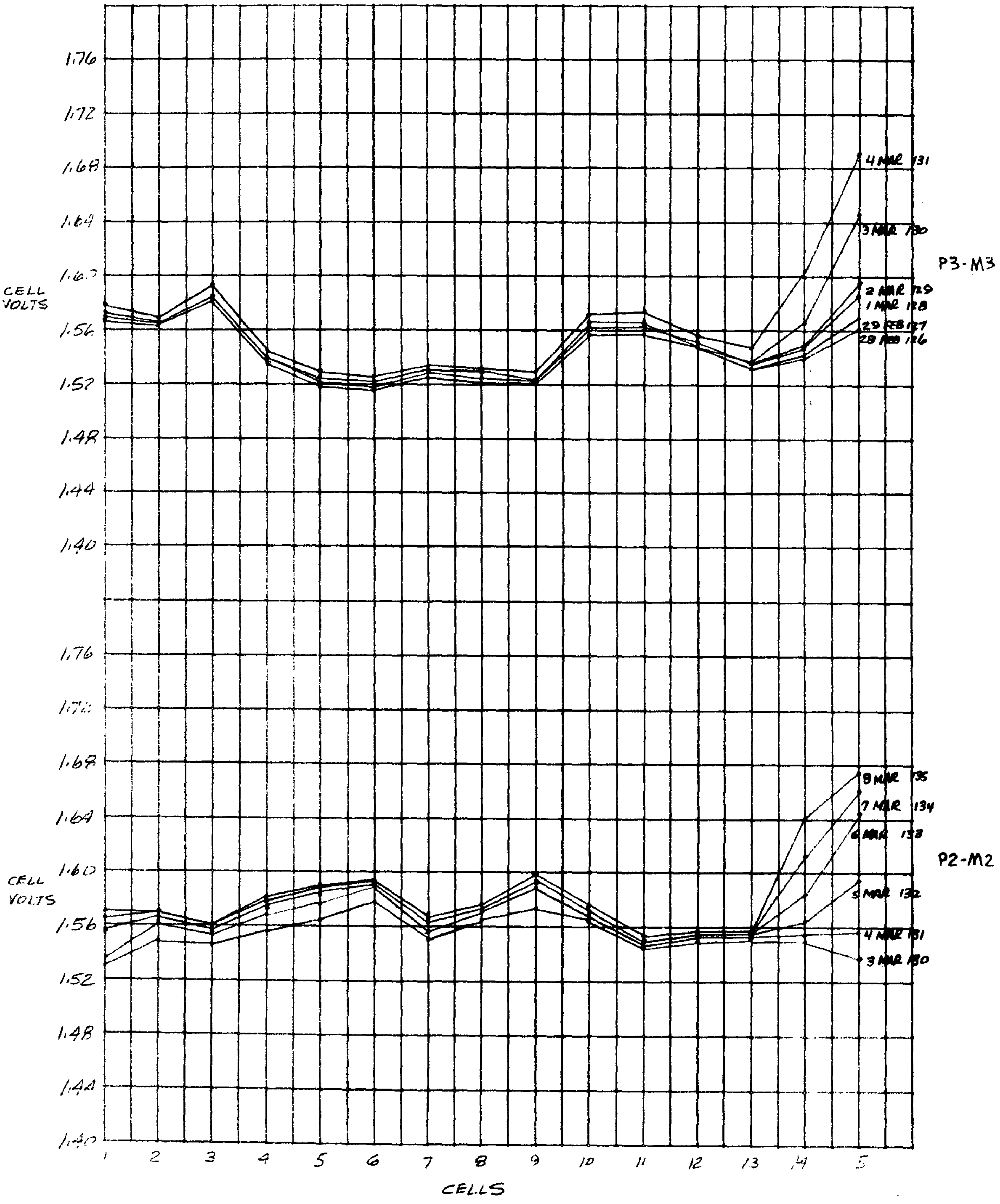
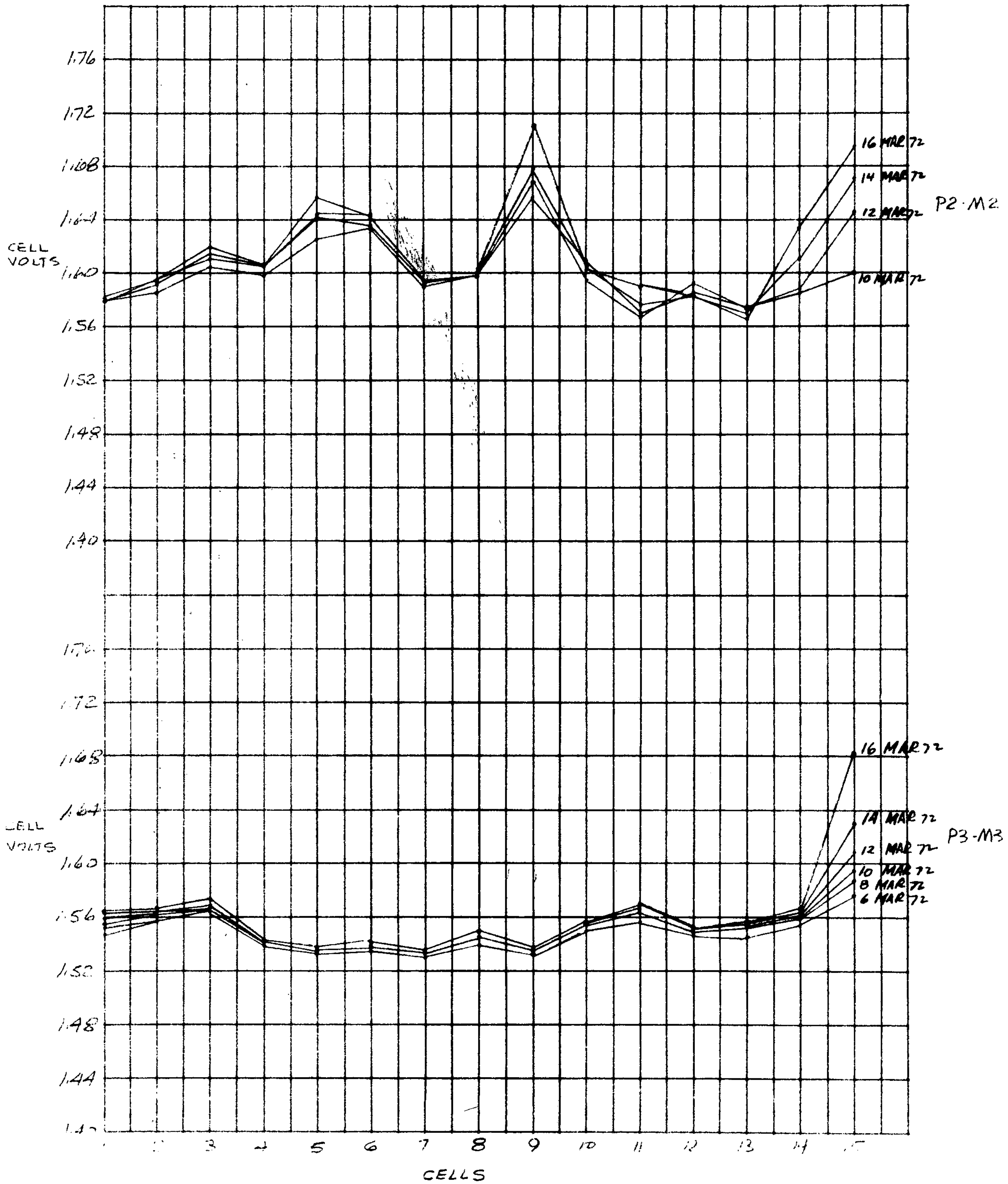


FIGURE 5-175 CELL VOLTAGE PROFILE

0000 READINGS ON INDICATED DAYS 11.3 AMPS

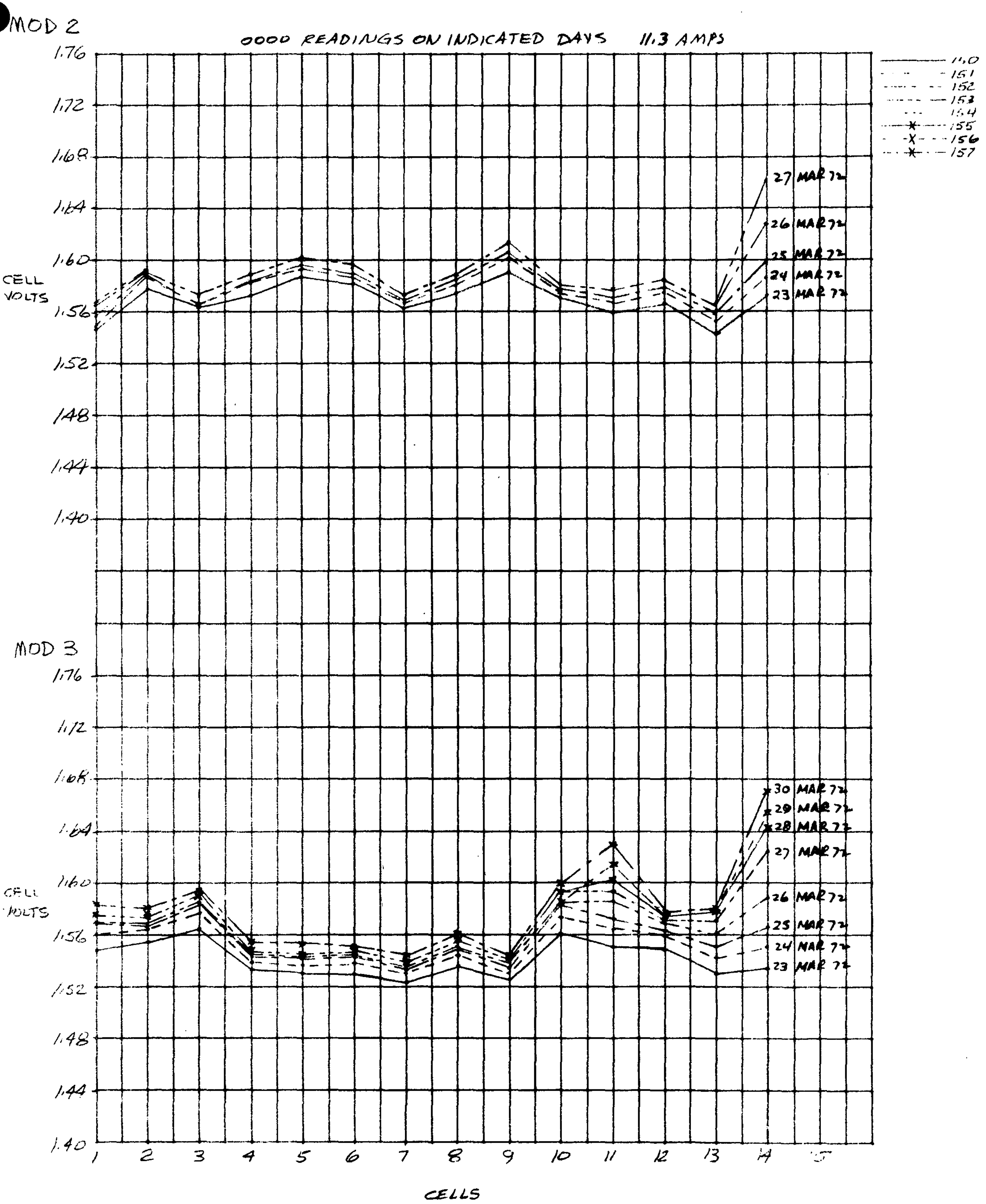


fold which connects to all cells. Bench testing with plastic tubing simulating the configuration of 4 cells and two fluids of different specific gravities revealed that most of the distilled feed water was rising in cell 15's water cavity, flowing across the top of the module in a common manifold and then entering into the cells from the top. It appeared that the excess flow of water through the water cavity of cell 15 was causing a decrease in electrolyte concentration within the cell and hence high cell voltages. Some of the low specific gravity fluid was observed to rise in cell 14's water cavity but only about 20% of the quantity rising in cell 15. Operation of the modules with 14 operating cells and using cell 15 as a liquid bypass (power disconnected) did not improve the operating duration of the modules. This profile of cell voltages for 14 operating cells and one bypass cell is shown on Figure 5-176. It is apparent that even with one cell acting as a bypass, electrolyte maldistribution is occurring in cell 14. The major concept to eliminate the electrolyte maldistribution problem would be to change the location of water feed to a point where gravity was not a problem and incoming feed water would not interfere with the outflow of trapped gas. Other concepts that might have minor favorable influence on eliminating the electrolyte distribution problem include: more frequent circulation of loop electrolyte to reduce the duration for back diffusion of KOH, shorter duration of circulation to reduce washout effect, reduce concentration differences between electrolyte loop and cell matrices.

For the last week of the test the matrices were charged with 35% KOH and the loop with 32% KOH. Operating duration was not improved by this change as the failure mode was still excess voltage in cell 15 due to KOH washout. However, cell voltages in most other cells were more stable and at a slightly lower level. This implies that the higher concentration in the electrolyte matrix promoted improved conductivity, thus less IR drop and lower voltages. Admittedly, the improvement was very minor.

Because of the uniformity of performance of all cells except cells 14 and 15, it is evident that a change in the water feed configuration is required to eliminate the electrolyte washout of these cells. With water feed at the

FIGURE 5-176 CELL VOLTAGE PROFILE



top of the module and in a manner not to interfere with gas flow out of the module, improved performance of the modules should be obtained. This change requires a minor redesign which was not part of the present contract; hence, it could not be tried.

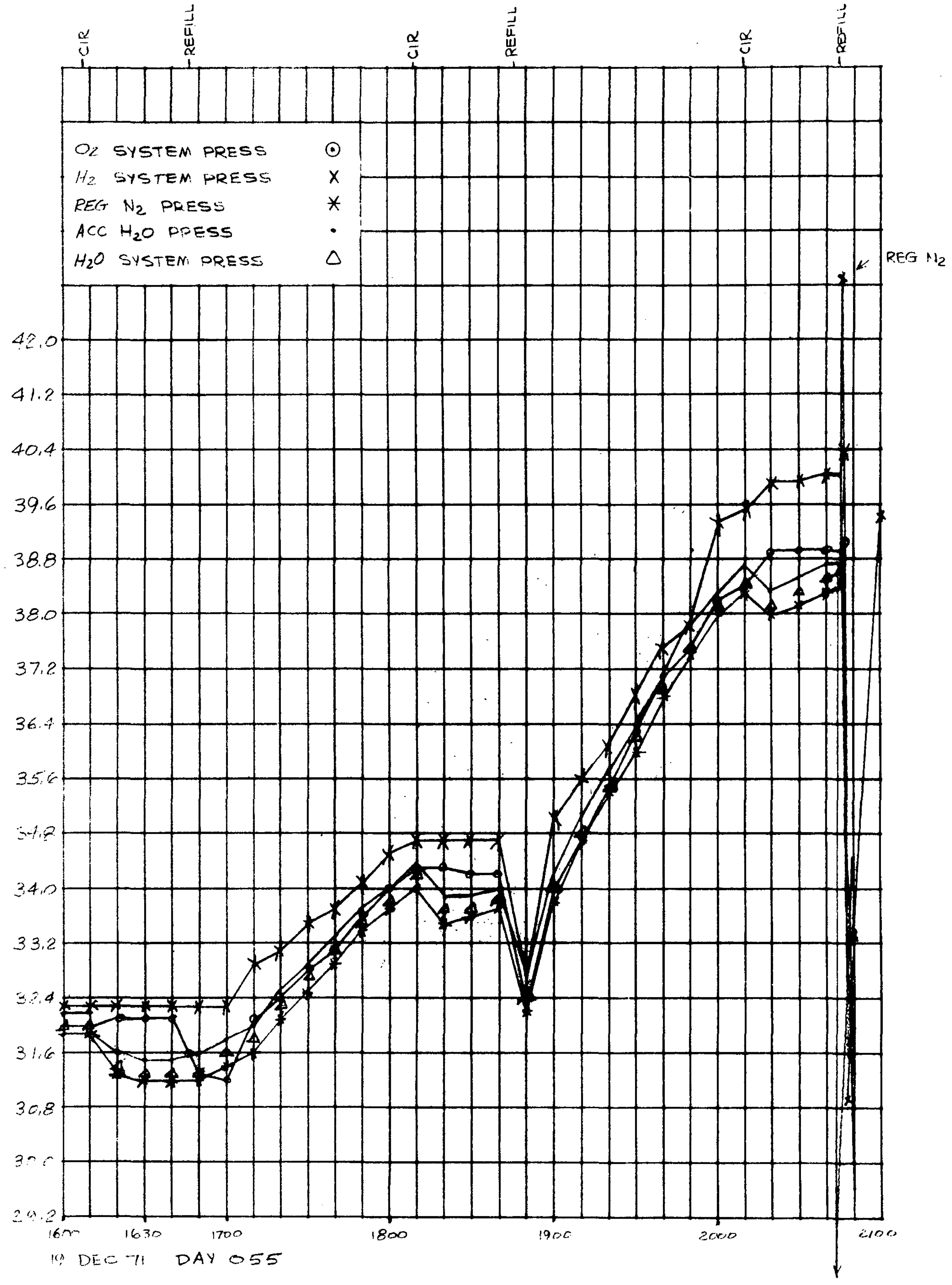
5.7.5 Pressure Control

During operation of the system it was deemed desirable that a supplementary panel of pressure gages be assembled and installed on the system to more accurately display small pressure variations. The panel was prepared and installed adjacent to the system. It consisted of 4 gauges: a differential pressure gauge (readable to 0.2 psig) to monitor differential pressure between feed water and hydrogen, a differential pressure gauge (readable to 0.1 psig) to monitor differential pressures between hydrogen and oxygen, a total pressure gauge (readable to 0.5 psig) for monitoring feed water or system electrolyte depending on setting of selector valve, and a total pressure gauge (readable to 0.2 psig) for monitoring hydrogen pressure. All gauges were located so as to read within a few inches of water the conditions existing within the modules. Conditions to be maintained on these gauges, showing values at the modules, were as follows:

- O_2 to H_2O: 1 psig minimum
- H_2 to H_2O: 1 psig minimum
  4 psig maximum
  2 - 2-1/2 desired
- H_2 to H_2O: (if salt bridge occurs): 1 psig minimum
  2 psig maximum
- H_2 to O_2: > 0 minimum
  < 2 psig maximum
  1 to 1-1/2 desired

Figure 5-177 shows the pressure conditions that existed on 19 December between 1600 and 2046 when the system shut down due to out-of-tolerance pressure conditions. The rise in pressure after 1700 cannot be adequately explained and is not understood. On the morning of 19 December module 1 was removed from

FIGURE 5-177 PRESSURE VARIATIONS



19 DEC 71 DAY 055

the system. To accomplish this removal, it was necessary to reduce system pressure close to ambient, remove the module and then slowly increase system pressure to the desired level. This change was completed at about 1010 and, apparently, from the data the pressure stayed close to the preset levels for about 6 hours. After the 1644 water refill, the pressures began to rise and were strongly affected by the 1844 water refill. The system was shutdown at the 2044 water refill. Electrolyte circulations seemed to cause a stop in the pressure rise but only until the next water refill occurred (30 minutes later). All regulators were carefully checked but no unusual conditions were observed. This problem did not recur.

5.7.6 Electrolyte Temperature Profiles During Circulation

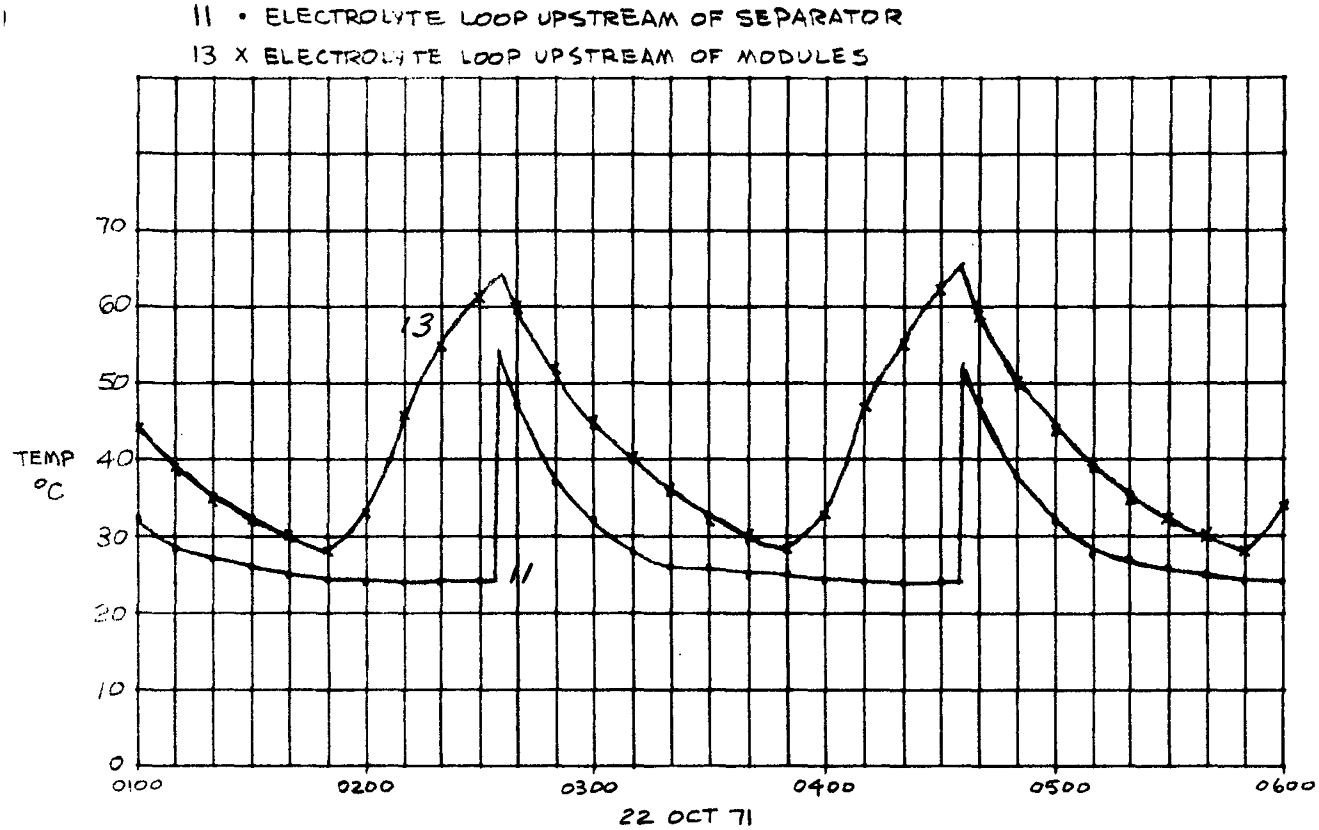
Figures 5-178 and 5-179 show temperature profiles occurring within the system during a series of circulation periods in early weeks of testing. Thermocouple 11 shows the condition of the electrolyte just upstream of the zero-g separator and thermocouple 13 shows the electrolyte temperature changes in the heated line just upstream of the modules. The vertical rise of temperature shown by thermocouple 11 represents the circulation period. Figure 5-179 represents the condition where the separator thermal box has more insulation than Figure 5-178. The effect of the increased insulation has been to cause a slight 1 to 2°K (1.8 to 3.6°F) rise in final temperature of thermocouple 13 but a drop of approximately 5°K (9°F) temperature of thermocouple 11.

5.7.7 Failure Analysis

Figure 5-180 shows the failure history of the SVFU as a function of test days. By the end of the testing the SVFU had experienced a total of 59 failures. As indicated by the figure, the majority of the failures occurred in the first half of the test. The majority of the failures occurring in the last half of the test were due to electrolyte maldistribution.

The comparatively low failure rate achieved during the first 25 to 30 days of operating time of the SVFU was achieved using modules of mixed designs. Eventually, this configuration was determined to be unrealistic because, under the operating conditions used, it had inherent defects such as uncontrolled transfer of electrolyte between modules, excessive stray electrolysis,

FIGURE 5-178 TEMPERATURE PROFILES



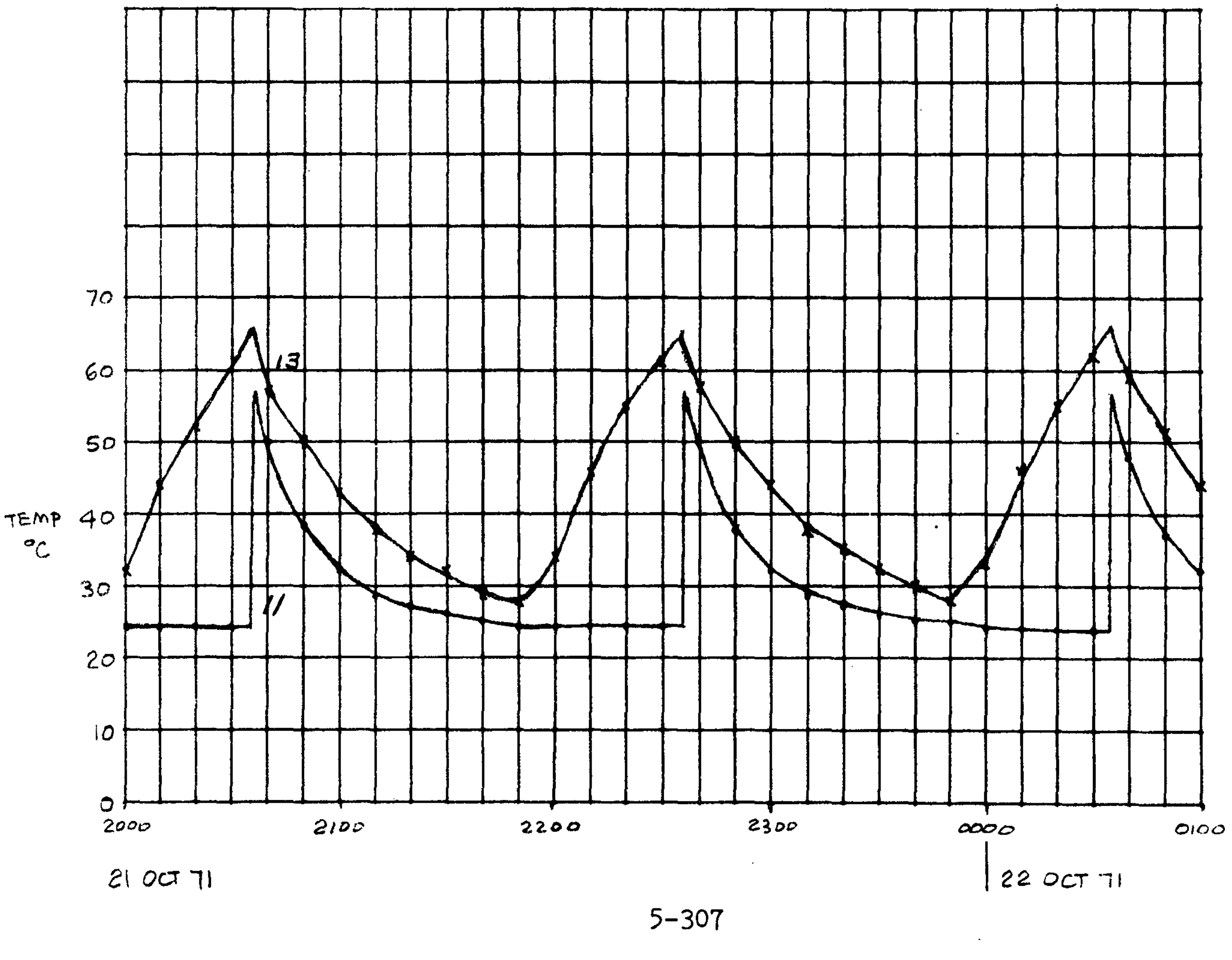
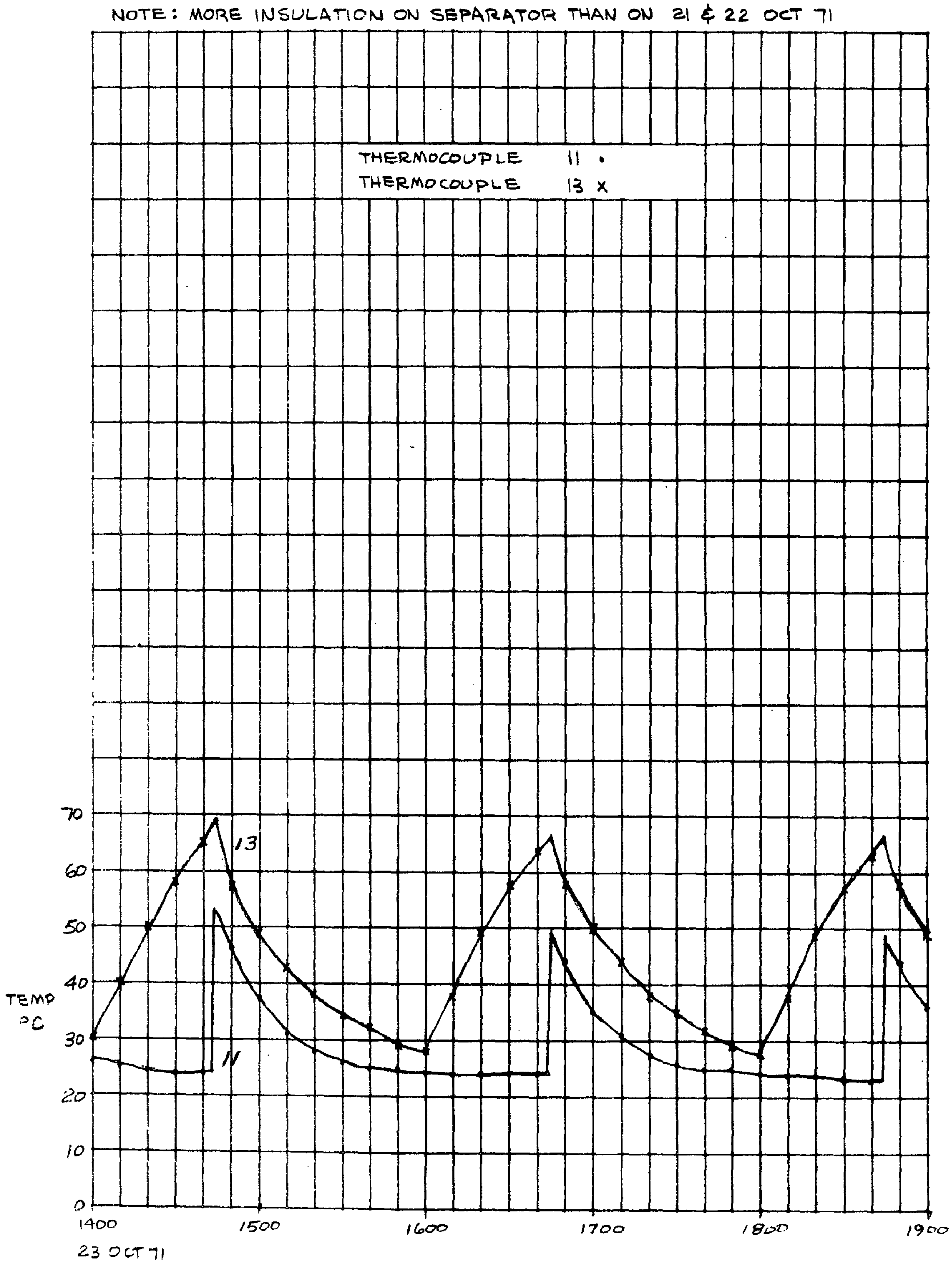


FIGURE 5-179 TEMPERATURE PROFILES



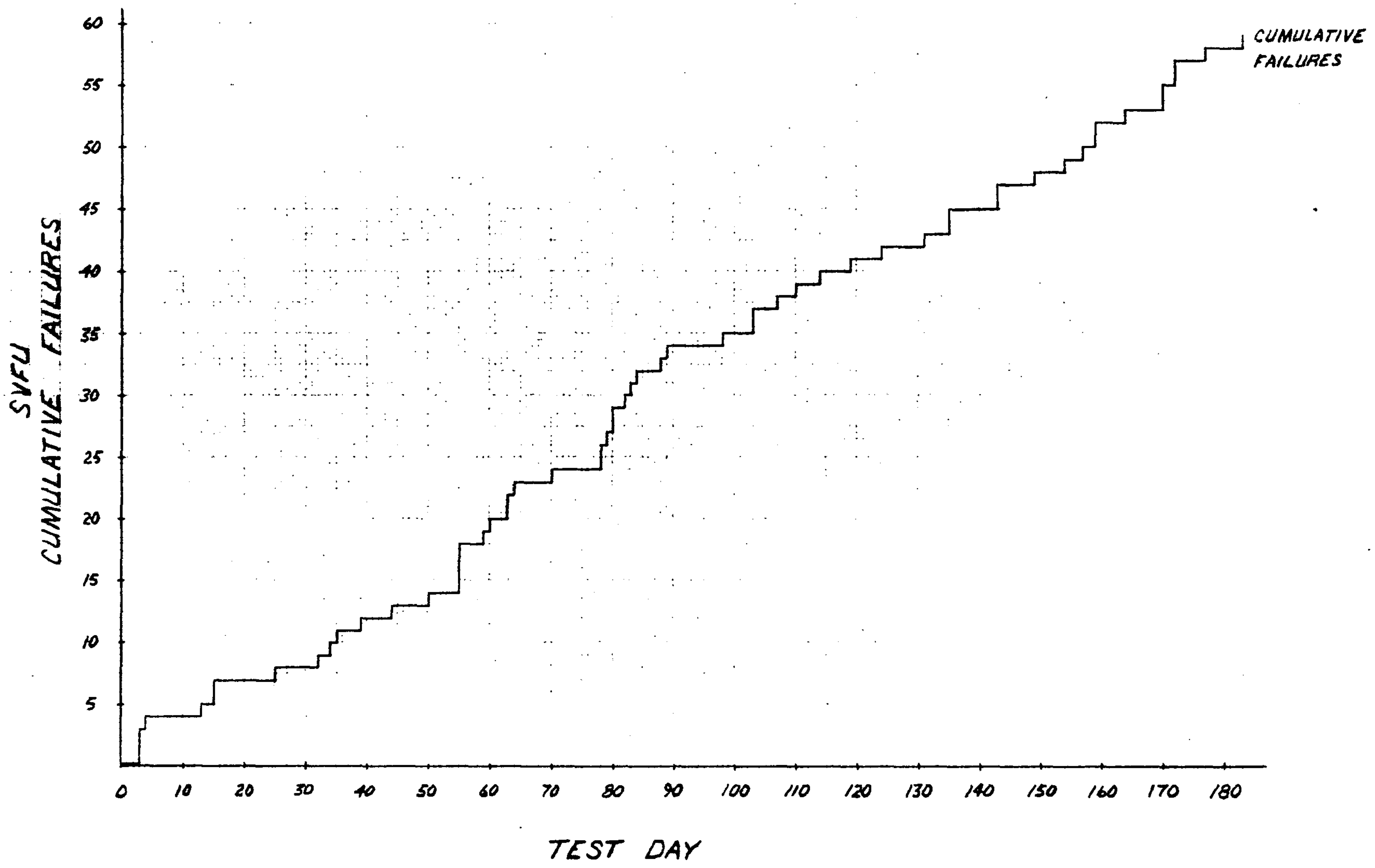


FIGURE 5-180 SYFU CUMULATIVE FAILURES

electrolyte bridging and shunt current losses. Between day 30 and day 90, the SVFU was operated in a series of modes necessary to solve electrolyte-distribution problems within the 1968 design modules, to stabilize gas-to-liquid differential pressures, to replace the accumulator with an improved design after a failure and to incorporate a 1-g gas-liquid separator. The unit was operated from day 90 to day 120 with continuous electrolyte circulation and generally at 70% of nominal current density while awaiting parts for final redesign. Operation after day 120 was representative of the system in the most favorable mode found. Failures occurring during this period were caused by fatigue cracks in the polysulfone structure of the cell or by undesirable electrolyte concentration gradients within the modules. These two failure modes persisted to the end of testing despite various attempts to control and limit their effect. It was judged that neither of these failure modes would be eliminated by continued testing under the ground rules of this test program.

Table 5-9 shows the SVFU failures that occurred during testing, the shutdown mode that was indicated by the data system, and the failure mode and the mechanism causing the failure as diagnosed from the data. Module shutdown meant that one or more modules were shutdown, but the system continued to operate on the remaining module(s). System shutdown meant that the system was shutdown because of a malfunction to hardware peripheral to the modules. If the modules were performing in a satisfactory manner at the time of system shutdown, no failures were listed under module shutdowns. If the modules were failing at the time of system shutdown, then a module shutdown was also listed. Analysis of the data revealed that module failures and system failures did not occur simultaneously; thus, the number of failures experienced is the sum of the data in the system and module shutdown columns.

Table 5-9 indicates that cell overvoltage caused 80% of all module shutdowns and 56% of all shutdowns. These shutdowns were caused by maldistribution of electrolyte within the cell matrices, electrodes, cavities and circulating loop of the system. Most of these shutdowns were caused by leaking check valves in the electrolyte-outlet line on each module. The next most significant problem was electrolyte washout due to density gradients in cells 14 and 15. The first problem was solved by isolating the modules with solenoid valves instead of check valves in the outlet line. The second problem was never eliminated during the remainder of testing. A series of changes were

TABLE 5-9
SVFU FAILURE SUMMARY

Test Day	Shutdown Mode	Failure Mode	Failure Mechanism	Total Number of Failures	Number of System Failures	Number of Module Failures	Remedial Action Taken
3, 4, 15, 34, 35, 55, 79, 80, 88	Cell overvoltage	Electrolyte maldistribution (EMD)	Check valves leak	15	0	15	Replaced 3 check valves with solenoid valves.
114, 131, 135, 143, 149, 154, 157, 159, 170, 177, 183,	Cell overvoltage	Electrolyte maldistribution (EMD)	Density gradient, electrolyte washout	13	0	13	Operated module in inverted position, operated module in 14 cell configuration. Varied concentration and circulation frequency.
124, 143, 172	Cell overvoltage	Electrolyte maldistribution (EMD)	Cracks in cells	3	0	3	Replaced ~ 12 cells.
44, 110	Cell overvoltage	Electrolyte leak	Instrumentation wire corroded loose	2	0	2	Reconnect instrumentation wire.
3	Manual	Operator error	Communications error	1	0	1	Module moved to different thermal box.
13	Module overtemperature	Operator error	Improper temperature controller settings	1	0	1	Corrected controller setting.
82, 83, 84, 103	Module overtemperature	No electrolyte flow	Pump magnet misalignment	5	0	5	Replaced circulation pump (once).
119	Module overtemperature	Excess heater time	Temperature controller stuck	1	0	1	Repair controller.
55	Differential pressure switch	Operator error	Improper pressure	1	1	0	Modified procedure.
55, 59	Differential pressure switch	Pressure out of tolerance	Improper limits	2	2	0	Reset limits.

TABLE 5-9
(continued)
SVFU FAILURE SUMMARY

Test Day	Shutdown Mode	Failure Mode	Failure Mechanism	Total Number of Failures	Number of System Failures	Number of Module Failures	Remedial Action Taken
89	Power loss	Tripped facility circuit breaker	Electrical short external to SVFU	1	1	0	Repaired short, connected SVFU to different circuit.
15	Two-minute delay expired	Peripheral equipment failure	Plug loose or not properly seating	2	2	0	Replace or reseat plugs.
25	Two-minute delay expired	Operator error	Improper procedure	1	1	0	Modified procedure.
39	Two-minute delay expired	Computer malfunction	Dropped octal memory bit	1	1	0	Reload computer.
64	Self-test signal not recognized	Computer malfunction	Electrical noise	1	1	0	Reloaded computer.
164	Two-minute delay expired	Magnetic tape coupler malfunction	Bad resistor in magnetic tape coupler	1	1	0	Replaced resistor.
172	Two consecutive sync errors	Magnetic tape coupler failure	Bad transistors in magnetic tape coupler	1	1	0	Replaced two transistors.
EQUIPMENT FAILURES NOT RESULTING IN MODULE OR SYSTEM SHUTDOWNS (FAILURES)							
32		Accumulator leak	Pinholes in bladder	1	0	0	Replaced accumulator.
50		Visual inspection of quick disconnect	o-ring deterioration	1	0	0	Replaced Q.D. o-rings.
78		Feed water leak	o-ring deterioration	1	0	0	Replaced Q.D.
70		Separator leak	Cracks	1	0	0	Replaced separator.
78		Limited electrolyte flow	Pump clutch disengagement	6	0	0	Thought to be thermal problem, lowered input heat. Later changed pump (see above).
98, 107		Regulator leaks	Split diaphragms	2	0	0	Replaced diaphragms.
135		No module 2 shutdown when required	Integrated circuit failure	1	0	0	Replaced integrated circuit.

made to improve electrolyte distribution stability. In addition to positive isolation by solenoid valves, these changes included changes in circulation frequency, duration and flow rate and using different KOH concentrations in the circulation loop from that used in charging the modules. Water feed was tried at the top and bottom of the modules to try to overcome the effects of different densities of water and KOH. It is concluded that the major concept to eliminate the electrolyte maldistribution problem would be to change the location of water feed to a point where gravity was not a problem and incoming feed water would not interfere with the outflow of trapped gas. Other concepts that might have minor favorable influence on eliminating the electrolyte distribution problem include: more frequent circulation of loop electrolyte to reduce the duration for back diffusion of KOH, shorter duration of circulation to reduce washout effect, reduce concentration differences between electrolyte loop and cell matrices.

The next major problem encountered caused only three module shutdowns but resulted in 12 cells being replaced. This was due to leaks in the cells that either allowed excessive quantities of KOH to leak out of the system or allowed the KOH to come in contact with the heater wires in the cells. This resulted in stray electrolysis, excess gas in the cell water cavities, reduced vapor transfer, drying of electrodes and matrices and finally overvoltage in the cell. The cracks that developed within the polysulfone structural sheets of the cells appeared to be fatigue failures that were caused by thermal cycling, mechanical loading during the numerous reassembly after repairs, or stresses developed during fabrication. These minute cracks permitted fluid to leak from the cell manifold to the heater wires or thermocouple wires or to the external periphery of the o-ring grooves, then out of the module.

The "two-minute delay expired" indication was a fail-safe communication link between the data acquistion system and the computer. If the data acquistion and the computer did not communicate within 2 minutes, the computer sent a signal to shutdown the SVFU. This was necessary to prevent damage to the SVFU in the event that a malfunction occurred in the system when the computer and Dymec were not communicating.

5.7.7.1 Cells

The frequent module assembly and disassembly operations conducted by the test engineers identified some major shortcomings in the design of the cells that should be briefly discussed. An excessive amount of repair time was wasted soldering and unsoldering of all the electrode screens and heater tab connections. The process could be made much more efficient by other methods. Heaters within the cells were frequently lost because of poor and unreliable junctions between the copper sheets and the nichrome wire. The use of materials that were compatible with KOH would have improved the situation considerably. A more rugged connection between the heater tabs and the heater busses would also have been an improvement.

Cracks in the cell cover sheets and heater wire sheets were a significant cause of cell failure as was mentioned before. Eliminating the necessity of heater wires would be a significant improvement in eliminating stray electrolysis caused by KOH coming in contact with the heater wires. Cell temperatures could be obtained by other methods. The second major cause of cell failures was leakage through o-ring grooves. This is partially due to the o-ring grooves not meeting o-ring manufacturer's groove design specifications. The new cells had machined grooves that were closer to design specifications than the old cells. The 1968 design cells had laminated o-ring grooves that were not concentric, did not have smooth surfaces and were not the proper depth. To compound the problem, the cells were not uniform in thickness. This necessitated stocking 3 different cross-section diameter o-rings to meet the different cell variation to get a good seal. Some cells even required shims to ensure that the center of the cell received the proper compression when assembled. Uniform thickness and uniform flatness would help considerably in improving reliability of cells from the standpoint of leakage of KOH. If unitized cells cannot be made that way then the concept of unitized cells should be eliminated. Unitized cells do have an advantage for space applications in that it is easier to handle 15 cells and 8 o-rings per cell than it is to handle 4 to 6 sheets per cell and 24 o-rings per cell. The failure analysis of cells indicates that additional work is required before these cells are ready for space applications.

5.7.7.2 Modules

Incorporating the improvements mentioned in the section on cells would also improve module reliability. Basically the modules need improvement in the area of packaging, thermal design and improved strength where tube connections are connected to the plastic spacer plate. Redesign of the modules to eliminate the plastic plumbing external to the modules would be desirable. Soldered connections on the module power leads, cell instrumentation wires, and heater manifolds frequently come apart due to corrosive action of leaking KOH. Use of a different type of connection in these 3 locations would eliminate that problem.

Two other problems that are related to module design and not specifically cell design are electrolyte circulation and makeup water feed. In the static feed concept, the cell matrix, the water transport matrix, and the electrolyte or water feed cavity are all initially charged with a constant concentration of electrolyte. As operation results, shifts in concentration occur within this electrolyte, causing gradients within the feed cavity due to mass transport mechanisms. A higher concentration will result in the water transport matrix than in the bulk feed fluid due to the vapor pressure gradient required for a certain water consumption rate. In the operation of an actual static feed cell, gases from various sources may accumulate within the feed cavity. This gas buildup will result in a liquid volume decrease and, with a given amount of KOH, the concentration of the feed compartment will rise. To remove this gas buildup, the system is designed to circulate the feed fluid through the compartments causing the gas to be flushed out from the feed compartments and restoring the cells to their original concentration levels. It therefore can be expected that, in applications where gases are liberated within the feed compartment, a continuous circulating mode will result in the most steady-state condition obtainable for a static feed cell. In a cell where no gas generation within the loop or in the cells is attained, the most steady-state condition can also be attained by never circulating fluids through the feed compartments. Therefore, either continuous circulation or zero circulation result in the most steady-state operation possible with a static vapor feed cell. In systems where gas buildup occurs and continuous circulation is not utilized, intermittent circulation will cause gas removal from the individual cells. Duration and frequency of the circulation is a function of cell construction and amount of gas buildup, respectively. In a module, of the A-C design subjected to intermittent circulation of the liquid in the feed compartments, a certain electrolyte maldistribution results in cells 1 through 15. An optimum frequency and duration of circulation possibly exists to a) remove gases from the compartments and b) equalize the electrolyte concentration within all cells. The equalization of concentration would demand, generally, longer circulation duration at greater intervals. A minimization of this problem can be attained by constructing a water electrolysis module with a separate manifold system for cavity circulation and a separate manifold system for feed water addition. Also, experimentation through testing would be required to identify the correct location for the two separate manifolds - water feed and cavity circulation, whether it is for 1-g or null-gravity operations.

5.7.7.3 Stray Electrolysis

As was pointed out above, accumulation of gases within the liquid feed water loop of the static vapor feed system causes performance degradation and possible system failure if gas accumulation is excessive. There are three basic sources for gases accumulating in the feed compartment.

1. Stray electrolysis within the liquid passages,
2. Release of dissolved gases from the makeup feed water and/or condensate return, and
3. Crossleakage of hydrogen into the feed compartments.

Crossleakage of hydrogen into the feed compartments can result from a cell failure due to structural inadequacies or due to water transport matrix dryout caused by gas generation or accumulation due to the other two causes. Hydrogen crossover, therefore, is either a structural failure or indirectly caused by the other two and needs no further discussion.

Of the two remaining gas sources, stray electrolysis and dissolution of dissolved gases, the first can reach extreme magnitudes in gas volume generation and the latter is typically fixed by the total amount of water processed. At 9.35×10^4 N/m^2 (700 mm) pressure and 297°K (75°F), 17.5 cubic cm of air can be dissolved in 1 liter of water which results in 17.8 cubic cm of air per kg of water (8.09 cubic cm per pound). Therefore, the maximum rate due to dissolved gases can be established which, for a single AC module having 15 cells and processing 1.36 kg (3 pounds) of water per day (11.3 amps) 24.3 cc/day/module will be liberated (if the feed water were saturated with air). The water saturated with product gases and returning from the condenser was not included but could amount to an additional 20% of nominal operating conditions because of different temperature and pressure conditions. Aside from the condensate water, which is saturated by the product gases, the feed water used to make up for that which is electrolyzed would typically be considered saturated with air or possibly nitrogen at ambient temperature and pressure, the values of which were cited above.

The solubility of gases in water is a function of absolute pressure, temperature and the type of gas involved. If a gas mixture is used, the partial pressures of the gases may become important. CO_2, for example, has a much higher solubility in water than air; however its presence in a basic electrolyte system is highly undesirable and would typically be taken care of by an ion exchange resin. The solubility of air or other gases in electrolyte is a function of the electrolyte concentration. The higher the concentration, the lower the solubility of the gas in the aqueous solution. Typically, the solubility of gases in 35% KOH is decreased by about a factor of 10.

To preclude gases from being evolved from the feed water as it enters the feed cavity at the elevated temperature of module operation and the decreased solubility due to the presence of KOH, the total operating pressure can be raised by a ratio, with respect to ambient pressure, equivalent to the loss in solubility by the combined effects of elevated temperature and presence of electrolyte. Under these conditions, dissolved gases will not come out of solution within the feed cavities. This concept has been demonstrated on single cells but remains to be proven in the system. However, it should again be emphasized that the maximum amount of gas from this source is fixed and based on the initial conditions of the feed water and the amount of feed water and condensate water processed.

The most detrimental source of gassing can result from stray and/or intercell electrolysis which has been experienced in this testing. Since gas evolution by electrolysis requires a metallic surface as an electrode, the elimination of any such parts within a liquid loop is of utmost importance. When they cannot be completely eliminated, they must be minimized. The rate of stray electrolysis is a function of the total driving potential, i.e., the voltage that is available between two metallic surfaces contacted by a common electrolyte media. The distance between metallic parts or hence the resistance created by the electrolyte will also affect the amount of gases liberated for a given driving potential. To eliminate this driving potential, a significant rule is to maintain external parts that contact common electrolyte at an equal electrical potential. A designer of a static vapor feed electrolysis module must eliminate all metallic parts that contact the feed water directly within this module. Even though these parts are eliminated, the cathode electrode of each cell can act as a gas-evolving electrode with respect to a metallic part external to the module but contacted by the electrolyte loop. The path between the cathodes and the external metallic part that contacts the electrolyte is created by liquid and salt bridging from the cathode to the water feed compartment. Hence, an external metallic part contacting the electrolyte sees a variety of electrical potentials in a module connected electrically in series. For example, a module operating at 22 volts DC has available a maximum driving force of either plus or minus 22 volts if the external metallic parts are grounded at either the plus or negative terminal of the power supply to the module. It is, therefore, only possible to limit this driving force to half the total module voltage if the external metallic parts in the electrolyte loop are kept at one-half the total module voltage above the most negative cell within the module. In the above example this would correspond to maintaining the external loop at +11 volts with respect to the negative terminal of the module. If the external parts must be grounded at either the most positive or most negative potential of the module, the most positive is preferred. This is so that the metallic parts in the loop become an oxygen evolving electrode and thus only one-half the volume of gas is generated for a given stray current flowing. Metallic parts separated from the module by non-conductive lines containing water will require more than typically 10 to 20 volts to cause electrolysis to occur. Only the presence of KOH contacting the metallic parts will cause stray electrolysis at those potential levels.

During the acceptance testing program at LSI, individual modules were run in a continuously circulating mode with 35% KOH. In the 1968 design modules, no gas accumulation was noted in the 1-G type transparent, external gas separator. The presence of the teflon membrane in the 1968-design modules typically could be considered prohibiting excessive bridging between the cathodes of the individual cells and the external metallic loop components. These components were kept at one-half the average module voltage above the negative terminal. With the bridging being negligible, stray currents were highly limited. No gases were observed that could have resulted from dissolved gases contained in the feed water. The feed water was not specially treated other than having passed through a deionized column system for removal of dissolved CO_2. The modules were typically operated at twice atmospheric pressure and at a maximum the water could have been assumed saturated at one atmosphere. These findings seem to support that not all dissolved gas will come out of the solution within a module and that dissolved gases will be evaporated into the cathode compartments at the liquid vapor interface where the water vapor is formed.

The 1970 design cells contained in modules 4 and 5 caused consistent gas accumulation in the external separator (with continuous circulation). This gassing must have been a result of stray electrolysis, since electrolyte bridging is easier in the 1970 cells due to a lack of teflon membranes. The source of the gassing in the 1970 design cell was verified. With the modules installed, the hydrogen compartments were pressurized with 2.06×10^4 N/m^2 gage (3 psig) hydrogen above the water pressure and the water cavity fluid circulated. No bubbles appeared in the external transparent separator. When current was started, bubbles formed and were observed in the stream entering the separator. When current was stopped, bubbles ceased to form, identifying the source of gassing as stray electrolysis. The gassing rate of module 5 was approximately 25 scc/hr for its 100 hour acceptance testing. Module 4 was gassing at a rate of approximately 50 scc/hr. It should be noted that module 4 was found to have a leak to a heater tab resulting in possible increased gassing rates. The 25 standard cc/hr of gassing observed in module 5 during its acceptance testing can be compared with a 2 cc/hr observed during the static feed mode test over a 70-hour period. Based on the total water consumed and required for humidification for the 70 hours, the total dissolved gases that could have been carried into the module could account for 1.2 cc/hr. The reduction in gas accumulation with the module can be attributed to the high resistance path for stray electrolysis with the prolonged presence of water in the module feed lines, thus isolating external metallic parts from the internal electrodes (cathodes).

During the 182-day test stray electrolysis was caused by a variety of problems. These included: KOH in contact with heater wires external to cells and/or within the cells, KOH in contact with external plumbing and, the coolant loop shorted to earth ground. When all of these sources were isolated the gas generation rate within the water cavities of the cells was reduced to less than 0.5 cc/hr/module.

5.7.7.4 Equipment Failures

Most major equipment failures were described in earlier sections of the SVFU discussion. These failures included: a) replacement of the zero-g separator due to excessive leaks and sealing problems with a 1-g separator that was heated externally, b) replacement of flow-through accumulator due to a leak in the bladder with an improved design, c) replacement of diaphragms in the regulators due to fatigue failure, and d) replacement of the electrolyte circulation pump due to misalignment of the driven magnet and worn o-rings.

5.7.8 Product Gas Analysis

Analysis of output gases from both systems were to be measured as follows: 2 samples on first day, 1 sample on day 2, 3, 5, 8 and 15 and 1 sample at 2-week intervals thereafter. Due to the problems encountered in the early days of the test, gas sampling, in accordance with the above schedule, was not performed. The first gas sample was withdrawn on day 9 and was analyzed for O_2 and N_2 in H_2; H_2 and N_2 in O_2 and organic contaminants. The data collected at each sample period is shown on Table 5-10. The source of the N_2 in the H_2 sample on 3 November is not known but it is believed to be contamination of air occurring during sample taking. A revision in the procedure to allow a longer flush of the sampling line before taking the sample and to take the sample just before it was to be put into the gas chromatograph was used to eliminate N_2 contamination. Any wait time on the bench with no pressure on the syringe plunger tended to allow air contamination. Organic contaminant analysis during checkout testing showed only one peak which was identified as ethylene dichloride at a level much less than 1 ppm. This is the agent used by the manufacturer to bond together the layers of polysulfone in each cell.

5.7.9 Bubbler Water Analysis

During the testing measurements were to be made to determine the extent of KOH carryover from the electrolysis system by monitoring the pH change of water in bubblers downstream of the unit. The schedule called for

Table 5-10

PRODUCT GAS SAMPLE DATA

	SVFU					
	Product O_2			Product H_2		
Date	N_2%	H_2%	Organic	N_2%	O_2%	Organic
3 Nov 71	N(1)	N	N	1.34	0.2	N
10 Nov 71	N	N	N	N	N	N
11 Nov 71	--(1)	--	--	--	--	--
24 Nov 71	N	N	N	N	N	N
8 Dec 71	0.2	N	N	0.20	0.06	N
23 Dec 71	N	N	N	N	N	N
6 Jan 72 (2)	--	--	--	--	--	--
19 Jan 72 (2)	--	--	--	--	--	--
31 Jan 72	0.70	N	N	0.52	0.08	N
2 Feb 72	N	N	N	N	N	N
15 Feb 72	N	N	N	0.4	N	N
1 Mar 72	0.2	N	N	0.4	0.08	N
15 Mar 72	N	N	N	N	N	N
29 Mar 72	N	N	N	N	N	N
12 Apr 72	N	N	N	N	N	N
25 Apr 72	N	N	N	N	N	N

NOTE: 1. Sample not taken denoted thus "--". No contaminants detected denoted thus "N".

2. SVFU not operating 6 Jan 72 or 19 Jan 72.

testing weekly for the first month and then once every 4 weeks until the end of the test. Table 5-11 shows the results of this analysis. The initial pH of the water in the bubblers was 6.7. At the end of 3 weeks of checkout testing and performance/endurance testing the pH of the water was 9.15 in the O_2 bubbler and 9.20 in the H_2 bubbler. The rise for the next 2 weeks was very gradual. On 30 November the liquid carryover traps on the H_2 and O_2 lines downstream of the condenser were observed to be full of liquid. This caused some KOH to be carried over to the bubblers. Measurements of the actual values were made on 8 December and carryover was evident due to the color change in the bubbler water. After shutdown of the system the bubbler water was dumped and the bubblers cleaned and refilled with distilled water, pH = 6.4. All lines between the carryover traps and the bubblers were also flushed with large quantities of distilled water. Evidently the cleaning of the lines was inadequate as on 23 December the H_2 bubbler water had a pH of 9.1 and the O_2 bubbler water had a pH of 10.75. Considering this significant increase after only 4 days of operation (16 through 19 December) it is felt that comparing these values with previously recorded data would be misleading. These values would be considered baseline data and changes recorded subsequent to these values would be used for comparison purposes. From 23 December on the bubbler water pH values remained relatively constant. A slight down trend was evident in both the bubbler pH values implying that more KOH was being taken out of the bubblers by the effluent gas than was being added by the system. The 7.4 reading from the O_2 bubbler on 12 April appears to be bad data. A review of all pH readings indicates that this bubbler should have a reading closer to 10.5 - 10.6 as was obtained on 25 April. The 12 April O_2 bubbler sample was checked 3 times and the meter was checked against a known standard. Everything seemed correct. Unfortunately, a second sample was not taken from the bubbler for analysis and it is possible that the first sample was taken too soon after adding the 300 cc of distilled water to bring the water level up, thus incomplete mixing existed and the sample was drawn from the unmixed portion of the container.

Table 5-11

PRODUCT GAS BUBBLER DATA

	SVFU	
Date	O_2 Bubbler	H_2 Bubbler
9 Nov 71	9.15 (1)	9.20
15 Nov 71	9.40	9.40
22 Nov 71	9.55	9.35
8 Dec 71 (2)	11.85 (2)	8.45 (2)
23 Dec 71	10.75	9.10
18 Jan 72	10.70	9.20
31 Jan 72	10.65	9.20
15 Feb 72	10.60	9.10
13 Mar 72	10.50	8.80
12 Apr 72	7.40	8.90
25 Apr 72	10.60	8.80

NOTE:

1. Numbers shown indicate pH of bubbler water
2. 8 Dec 71 SVFU bubbler pH check was performed due to contamination of SVFU O_2 and H_2 bubblers. Bubblers were cleaned and refilled with water having a pH of 6.4 after the 8 December 71 check.

A chemical test was performed to determine the approximate amount of KOH that would have to be added to a bubbler to raise the pH from 6.8 to 10.5. The test indicated that 0.09 grams of KOH would be required to raise 1 liter of water the designated amount. The O_2 bubbler on this unit contained about 1 liter of water, and the H_2 bubbler contained about 1 1/3 liters of water, hence the KOH carryover was quite small.

5.7.10 Gas Venting Data

Analysis of significant performance periods of all modules between 22 October and 1 November 1971 showed that the gas generation rate within the system was 0.2521 scc/ampere-hour of operation. Of the 13 samples taken, all ranged between 0.126 and 0.302 scc/ampere-hour except three samples. The three unusual samples were higher; between 0.312 scc/ampere-hour and 0.416 scc/ampere-hour. These occurred when modules had been added to the system. It is very probable that some gas was trapped in the modules when they were added to the system and that some gas was introduced to the system during the connection process. No stray electrolysis was observed in the system that could have caused the unusual values.

Venting excess gas from the separator was accomplished daily. Usually 2 ventings were required; the first was done just before the 0810 circulation and the second was done just after the circulation. This process permitted venting of all gas with minimum perturbation of the system parameters and enhanced the "hands-off" philosophy. Venting quantities during the analog control period averaged 170 scc's for an average operating level of 615 amp-hours per day. With 3 modules operating at 11.3 amps the gas vent rate averaged 280 scc's for an average operating level of 814 amp-hours per day. With only one module operating gas venting on 30 November equalled 130 scc for 271 amp-hours operation. These values are higher than they should be for having dissolved gases in the feed water and therefore reflect a significant quantity of stray electrolysis within the system.

Venting quantities when module 4 was operating alone were about 130 cc's per day, between the period of 30 November and 8 December. Later when modules 1, 2 and 3 were operating at 11.3 amperes each, the total vent quantity was about 185 cc per day. This value was expected to decrease even further after the stray electrolysis due to the separator was eliminated. When 3 modules were used early in January, the venting rate was about 125 cc per 24-hour period. Early on 20 January, module 1 was removed from the system and from then until the end of the month only modules 2 and 3 were used. The gas venting quantity dropped to an average of only 18 cc per day. During these 8 operating days, two ventings resulted in a gas quantity over 15 cc/day; the other 6 days were all less than 12 cc/day. The 30 cc vent was measured on 21 January, the morning module 1 was removed from the system, and the 70 cc vent was on 27 January, the day after system startup when some gas was trapped in the loop during startup. This data indicates that stray electrolysis was occurring within module 1 and/or a cross leak existed within the module. The new 1-g separator was used during this entire period.

The reduced venting quantity allowed a change in the frequency of venting on week days and week ends. Venting gas from the separator was accomplished once daily except on weekends when it is usually done 32 hours after the Friday vent and 40 hours before the Monday vent. During February only 2 modules were used. Analysis of the data indicates that venting during the first part of the month was very low, at a level of 5 cc/day for each module. When module 3 shutdown approximately 90 cc were vented. When operating alone module 2 vented approximately 30 cc/day. The implications are that there was zero or a very small amount of stray electrolysis in the modules early in the month, then module 2 developed an internal leak between the water cavity and cell heater after the shutdown of module 3 that caused the increase in the gas vent rate. After the system modification and both modules were restarted, the gas vent rate increased to 112 cc/day for both modules or 56 cc/day/each module. Module 2 had not been disassembled during the period the system had been shutdown for modifications. Module 3 had been disassembled, however after module 2 failed module 3 alone exhibited a gas vent rate of 28 cc/day. This implied that there was stray electrolysis in both modules of approximately equal magnitude. Past experience indicated that there was probably a leak between the water cavity of a cell and the cell heater.

Analysis of the data collected in March indicates that the venting was fairly uniform during the month. When one module was operating the average venting was 79 scc. The few times the vent rate was higher than this was when another module was added to or removed from the system. The average vent rate with 2 modules operating in the system was 127 scc. This data implies that both modules were contributing to the gas accumulation in the electrolyte loop. Module 2 never operated alone, therefore the 79 scc average vent quantity is indicative of Module 3 performance. Module 3 was not disassembled during the month; consequently it is not possible to state whether or not electrolyte was in contact with any heater wires within the module. Module 2 did have one cell where electrolyte was in contact with the heater wire. After replacement of the bad cell and restart of the module the vent quantity did decrease about 25 scc per day to about 100 scc per day.

Early in April the venting rate was about 97 cc/day average or about 48 cc/day/module assuming both modules contributed evenly. Later, after the chassis voltage was increased by isolating the ground loop on the coolant plumbing, the gas vent rate decreased to about 70 cc/day or 35 cc/day/module. The failure of module 2, due to electrolyte contact between the water cavity and the heater wire, caused the vent rate to increase to 533 cc/day. Module 3 operating alone resulted in a gas vent rate of only 18 cc/day/module. After repairing module 2 and reinstalling it in the system the gas vent rate increased to 54 cc/day or about 27 cc/day per module. Evidently module 2 was still causing some stray electrolysis that was not eliminated by the repair. Module 2 gas generation rate in the water cavity appeared to be about twice the rate of module 3.

5.7.11 Mass Balance Data

Mass balance data was calculated for the 26-week periods that included all operating modes of the SVFU. This data is shown on Table 5-12. All data has been corrected for standard temperature and pressure. Additionally, the O_2 and H_2 gases produced have been corrected for water vapor content. Water used has been corrected to account for water vapor carried out of the SVFU in the product gas. Inaccuracies of the wet test meters have been included in the analysis. All calculations were performed in reference to weight in grams. A review of the data indicates that operations for the first 7 weeks resulted in a current efficiency of 85 to 98 percent (average 93.9%). This was caused by shunt current induced by salt bridging across the hydrogen cavity. The 1970 design lacked the Teflon barrier to prevent KOH transfer into the hydrogen cavity. Electrolyte bridging meant that there was direct liquid-liquid contact between the active-cell electrolyte and the feed-cavity electrolyte. Electrolyte bridging could not be observed visually but its pressure was identified by performing day-to-day mass balances on the electrolyte. Stray electrolysis, gas accumulation rates and calculations of current efficiency produced further evidence of electrolyte bridging. When the 1970-design cells were removed from the system and the system operated with one, two or three 1968-design modules the current efficiency increased to nearly 100% for the remaining 19 weeks of testing. This demonstrated that, although the 1968 design cells were current limited due to limited vapor transfer caused by the Teflon sheet restricting flow, the cell operated better than the 1970-design units. The 1970-design cells were not as current limited.

5.7.12 Energy Requirements

The energy requirements for 1, 2 and 3 module operation are shown in Figure 5-181. The specific energy requirements of the modules are shown by the line made of "x's" and are given as energy per kilogram of oxygen produced

Ta 5-12

MASS BALANCE DATA

Week	End Date	Corrected O_2 Production (grams)	Corrected H_2 Production (grams)	Corrected H_2O Used (grams)	Ampere-Hours	O_2 Produced / Amp Hr Ideal (O_2)	O_2 Produced / H_2 Produced	Total Gas / H_2O Used	Total Gas / Amp Hr
1	Nov 2	16809	2044	19619.7	3910.3	96.3%	8.21	96.0%	96.0%
2	Nov 9	15408	2186	19330	4053*	85.0%	7.05	91.2%	86.3%
3	Nov 16	24502	3018	27655.3	5726.9	95.8%	8.14	99.6%	95.4%
4	Nov 23	24340	2997	28324	5767.2	94.6%	8.11	96.7%	94.3%
5	Nov 30	20564	2488	Δ	4719.8	97.8%	8.27	Δ	97.3%
6	Dec 7	7937	971	10629Δ	1879.2	94.5%	8.17	83.6Δ%	94.3%
7	Dec 14	1649	201	2230.5	396.5	93.1%	8.20	83.1Δ%	92.8%
8	Dec 21	10889	1368	12828.5	2456.6	99.4%	7.96	95.5%	99.3%
9	Dec 28	14735	1886	19253	3392.5	97.4%	7.83	86.4%	97.5%
10	Jan 4	-0-	-0-	-0-	-0-	--	--	--	--
11	Jan 11	-0-	-0-	-0-	-0-	--	--	--	--
12	Jan 18	9261	1149	10809	2102.4	98.2%	8.04	96.3%	99.5%
13	Jan 25	4464	554	4801	1010.5	98.9%	8.05	104.4%	99.5%
14	Feb 1	10860	1349	12579	2438.8	99.9%	8.06	97.2%	99.5%

NOTES:

Lab. Temp - 22°C

Lab. Ave. Pressure - 765 mm Hg

* Week of analog control

Δ H_2O bladder failure. No H_2O weight or questionable water weight.

Table 5-12

MASS BALANCE DATA (Continued)

Week	End Date	Corrected O_2 Production (grams)	Corrected H_2 Production (grams)	Corrected H_2O Used (grams)	Ampere-Hours	O_2 Produced / Amp Hr Ideal (O_2)	O_2 Produced / H_2 Produced	Total Gas / H_2O Used	Total Gas / Amp Hr
15	Feb 8	8525	1052	9575.8	1907.9	100.0%	8.09	99.8%	99.8%
16	Feb 15	9388	1172	10553.3	2067.4	101.5%	8.00	100.2%	101.75%
17	Feb 22	2911	362	3308.1	666.7	97.8%	8.03	99.0%	97.9%
18	Feb 29	12037	1497	13614.5	2705.1	99.6%	8.04	99.4%	99.5%
19	Mar 7	13940	1734	15565.0	3117.7	100.1%	8.06	100.7%	100.3%
20	Mar 14	16677	2101	19108.9	3733.4	100.0%	7.94	98.2%	100.0%
21	Mar 21	10526	1313	12057.6	2361.8	99.8%	8.02	98.3%	99.6%
22	Mar 28	13322	1660	14860.7	3183.8 (1)	99.5%	8.02	101.0%	99.6%
23	April 4	12831	1602	14616.5	3089.4 (2)	99.3%	8.02	98.6%	99.5%
24	April 11	14509	1804	16274.7	3341.2 (3)	99.4%	8.04	100.2%	99.5%
25	April 18	10781	1331	12235.4	2430.6	99.2%	8.09	99.0%	99.3%
26	April 25	15372	1910	17364.2	3427.6	100.2%	8.05	99.6%	100.3%

(1) 2911.9 amp-hrs with 14 cell module
271.9 amp-hrs with 15 cell module

(2) 14 cell modules only

(3) 1159.4 amp-hrs with 14 cell module
2181.8 amp-hrs with 15 cell module

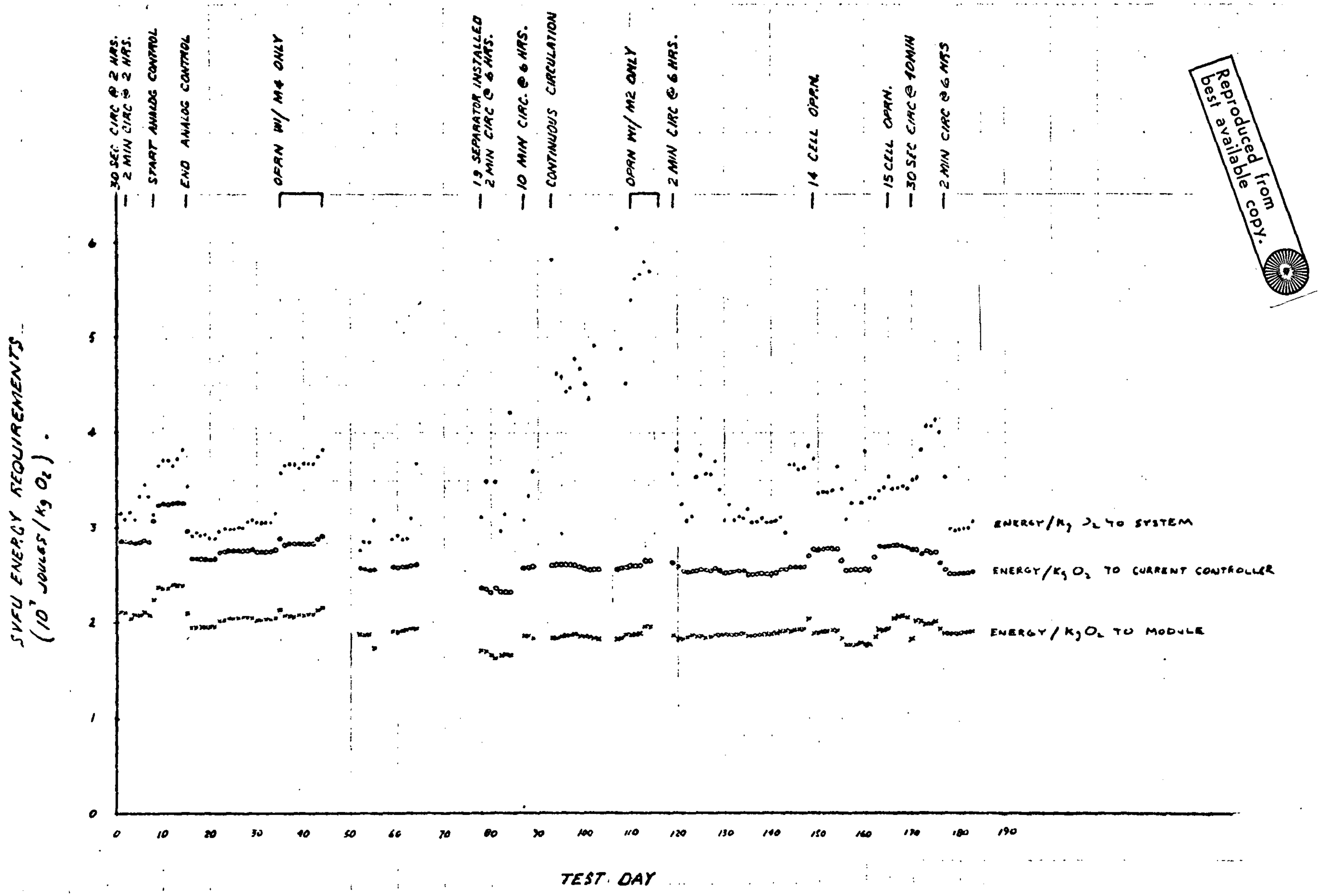


FIGURE 5-181 SVFU ENERGY REQUIREMENTS

GW 15MAY72

as a function of each test day. The value shown represents the average performance value for the module during the specific day as taken from the daily summary printout data sheets. A mixture of 1970 and 1968 design modules were used during the first 44 days. These modules were operated at 11.3 amperes during that period of time except for days 8 through 15 when the unit was operating under analog control. Energy requirements were higher in this period because each 1970 module O_2 production rate was reduced by 0.113 kg/day as a result of shunt currents induced by electrolyte bridging across the hydrogen cavity. Between test day 51 and 64 the system was operated with one, two, or three modules of the 1968 design at 11.3 amperes with intermittent circulation. Other combinations are shown on Figure 5-181.

The second line, comprised of open circles, represents the energy per kilogram of oxygen when the current controller energy is added to the module energy requirements. The dots on the curve represent the total system energy requirements. This includes parasitic power losses caused by cell and module heaters, fill and circulation pumps, and solenoid valve requirements. During intermittent circulation at nominal production, parasitic power represented approximately 16% of the total power requirements with 3 modules and 22% with two modules. Parasitic power consumed 43% of the total power during continuous circulation because of increased cell heater operation and circulation pump operation.

Table 5-13 shows the system component energy requirements for each week of operation. It is evident that operation with continuous electrolyte circulation caused a significant increase in power consumption. Observe the 14th through the 16th weeks, major increases in power are evident for: circulation pump, separator heaters, inlet tube heaters, and cycled module heaters.

Table 5-13

SVFU SYSTEM COMPONENT ENERGY REQUIREMENTS

Week	Refill Pump	Circulation Pump	Inlet/Outlet Solenoid Valves	Isolation Solenoid Valves	Separator	Inlet Tube Heater	Continuous Module Heaters	Cycled Module Heaters	Light Bulbs
1	137	548	32,236	22,480	30,982	21,100	18,800	9,020	4,840
2	137	548	32,236	22,480	30,980	21,100	21,600	8,800	4,840
3	137	548	32,236	22,480	30,980	21,100	24,600	3,795	4,840
4	137	548	32,236	22,480	30,980	21,100	24,600	3,243	4,840
5	137	548	32,236	22,480	30,980	21,100	20,600	4,025	4,840
6	137	548	32,236	22,480	30,980	21,100	8,220	3,863	4,840
7	29	117	6,908	4,820	6,640	4,530	1,710	1,282	1,035
8	69	275	16,118	12,400	15,480	10,555	11,440	5,980	2,420
9	101	405	23,793	16,590	22,860	15,580	15,100	6,970	3,570
10	0	-0-	-0-	-0-	-0-	-0-	-0-	-0-	-0-
11	0	-0-	-0-	-0-	-0-	-0-	-0-	-0-	-0-
12	104	418	24,561	17,130	36,800	16,082	12,900	9,900	3,688
13	44	880	10,362	7,230	15,370	6,785	6,360	5,615	1,556
14	36	9,220	25,328	17,670	47,300	33,150	13,720	79,800	3,805
15	29	7,470	20,531	14,330	55,400	26,860	10,080	61,400	3,083
16	39	10,040	27,631	19,280	99,700	36,150	10,110	74,300	4,150
17	14	3,562	9,786	6,820	24,680	12,810	3,770	14,340	1,469
18	137	548	32,236	22,480	28,900	21,100	12,420	13,830	4,840
19	137	548	32,236	22,480	28,900	21,100	13,550	12,700	4,840
20	137	548	32,236	22,480	28,900	21,100	16,150	10,010	4,840
21	133	533	31,276	21,800	28,050	20,460	10,220	7,620	4,690
22	136	542	31,852	22,200	28,550	20,840	14,000	9,660	4,780
23	137	548	32,236	22,480	28,900	21,100	13,070	12,280	4,840
24	120	480	28,206	19,650	25,300	18,450	14,380	12,000	4,230
25	270	370	28,974	20,200	26,000	18,950	10,460	4,150	4,350
26	45	180	31,660	22,080	28,370	20,700	14,920	19,930	4,760

NOTE:

1. Units for all components are 10^3 joules/week

2. Includes outlet tube heater and control rheostat. Also includes A/C boost heat supplied where applicable.

Redesign of the system could reduce the parasitic power requirements of a number of components. Higher packaging density with shorter plumbing circuits and better thermal insulation would reduce heater operating durations. Operation of inlet/outlet solenoids valves can be reduced if normally closed valves are used (rather than normally open valves as was required by the system modification), and decrease the frequency of circulation pump operation. Redesign of the separator can also reduce parasitic power requirements for heater circuits. Proper redesign, considering the adverse penalty of parasitic power consumption, can reduce this requirement by as much as 50%.

5.7.13 Nitrogen Consumption Data

Dry nitrogen gas is used as the pressurization gas on the feed-water accumulator and on all pressure regulators. During the first 96 days of testing the N_2 consumption rate was about 0.0743 m^3/day (2.63 ft^3/day). Subsequent to that day a leak started in one regulator that caused the consumption rate to go to about 3.2 m^3/day (113.2 ft^3/day). This rate continued until day 113. After the leak was repaired and all the diaphragms in all regulators inspected and replaced, as necessary, and the regulators adjusted for maximum sensitivity, the consumption rate of N_2 dropped to 0.021 m^3/day (0.74 ft^3/day). This low rate was maintained from test day 114 until the end of the test. This is a very realistic value for the system design employed in this testing. It is possible to eliminate all N_2 requirements on this system if O_2 is used for pressurization purposes. Nitrogen was selected for this test because of the problems encountered prior to the 90-day manned test. A single failure of the hydrogen back pressure regulator diaphragm allowed the H_2 generated gas and the O_2 pressurization gas to mix, thus creating a hazardous condition. Proper design, as was employed in the 100-hour checkout test at LSI, would eliminate the hazard and the necessity of N_2 pressurization gas.

5.7.14 System Equipment Modifications

A number of modifications were made to the SVFU during the 182-day testing period in an attempt to obtain new information, improve performance of the unit, automatically control certain operation and obtain new data to better understand operating phenomena. These changes or modifications were not basically related to failures or shutdowns of the system or modules which were discussed in section 5.7.7. These modifications are briefly described below.

- A pressure gauge panel was added to more accurately monitor the pressure differentials and absolute pressures of fluids in the system.
- Protective covers were added to a number of control knobs to prevent inadvertent movement of critically controlled set points.
- A rheostat was added to the circulating electrolyte pump to regulate the line voltage to 26 vdc rather than the 32 vdc applied to the unit.
- Fabricated and installed gravity type separator in lieu of alternate zero-g separator which had excess fluid pressure drop and developed leaks.
- Associated with the gravity type separator was the addition of a rheostat for controlling temperature of electrolyte within separator/reservoir.
- A temperature readout capability was added to allow operators to monitor the separator surface temperature.
- Added extra heater wire on electrolyte plumbing between module discharge and separator inlet.
- A rheostat was added to control the temperature of the heater wire added to the plumbing.

- Extra insulation was added to retain more system heat, especially during the period of continuous electrolyte circulation.

- Each time the circulation frequency and duration were changed the timers controlling the pump were adjusted. This was also done for the refill pump. A total of 11 changes were made.

- Wiring on the solenoid valves was changed each time the electrolyte was to be sequenced through the modules. This was done twice.

- Solenoid valves were installed on the module electrolyte discharge lines to replace leaking check valves. The solenoid valves were wired to open each time the electrolyte circulation pump started to flow electrolyte through the specific module.

- Jumper wires added on the 14-cell modules to allow readout of module voltage on the data system printout. This was done when cell 15 was disconnected electrically and used as a liquid bypass line. Later the jumpers were removed to operate the modules with 15 cells.

- Refill pump circuit was added to stop the refill pump when the pressure in the water accumulator reached 11 psig during a refill cycle.

- Wiring was added to provide readout on the data system printout of the SVFU chassis-to-ground potential.

5.7.15 Current Controller

The general purpose of the current controller electronics was to maintain the current to the electrolysis modules within preset maximums and minimums. Within this range the controller was to provide the option to vary the current inversely proportional to the pressure in an accumulator external to the electrolysis system in order to maintain oxygen production equal to oxygen usage. The current controller, provided for each module, monitored the current flowing through it and maintained a predetermined current regardless of line voltage fluctuations or variations in voltage required by the module. The current controller receives control inputs from two sources - the oxygen discharge pressure transducer and the manual current setting for each current controller located on the front panel of the unit. At the nominal current of 11.3 amperes, the efficiency of the regulator is 74% in other words, 74 percent of the power entering the current controller reaches the modules. At 8 amperes the efficiency of the current regulator is 71%. These efficiencies represent the optimum values which may be obtained for series regulator circuitry for the current range employed in the subject system. The current controller did perform very well during the 182-day test period. Failures were described in section 5.7.7. Refurbishment of the current controller for the 182-day test was accomplished under the sponsorship of McDonnell Douglas Astronautics Company inhouse capital funding and consequently emphasis was on improvement of reliability, low cost and simplicity and not on obtaining the most efficient controller possible. It is recognized that improved regulator efficiency may be obtained by employing another regulation technique. The most promising high efficiency, solid-state component, current regulator for the current range of interest (up to 14 amps) is the switching regulator. An efficiency exceeding 80% may be obtained with this type of regulator reducing the system power consumption and heat generation correspondingly.

5.8 Maintenance

The design of the SVFU was most adequate from the standpoint of accessibility for maintenance. All hardware was mounted on a central structure thus all equipment and wiring was readily available for corrective maintenance if the need arose. Equipment removal was simple and easy to accomplish. This was evident by the fact that a number of modifications were made to the system plumbing during the test. These were all accomplished without the necessity of removing other equipment to reach hardware that needed changing. Modules were removed frequently, the water accumulator was replaced, liquid-gas separator was replaced, pump timers and cam controls were changed frequently, all without any effect on other hardware. It is recognized that a higher packaging density will be required for spacecraft applications, but it should be emphasized that accessibility for maintenance, adjustment and control should be retained to minimize system down-time for these operations.

5.9 Instrumentation

The instrumentation installed on the front panel of the unit was adequate for all normal operations and all mechanical fault detection/isolation situations. This system was not designed with all safety shutdown instrumentation installed within the unit. A CDC computer was used for signal comparison and shutdown word initiation. If this system is to be connected to a spacecraft onboard checkout system the instrumentation was probably adequate. If the system is not to be part of the onboard checkout system, additional safety and shutdown instrumentation would be required on this system. Flight article quality assurance and the use of high reliability electronic components was not a requirement in the design of this system.

Due to the fact that a large number of problems were experienced by this system prior to and during the 90-day test, the system redesign for the 182-day test incorporated more instrumentation than existed earlier in order to better understand the phenomena occurring within the system and to aid in troubleshooting. After all the anomalies are eliminated the final design may very well use less instrumentation than was used in this test program.

Greater sophistication in electronics would probably justify a certain amount of signature analysis of the circuitry. Thus the operator would have a much better indication of the status or changing status of a circuit or circuits. Troubleshooting time would be reduced considerably and impending failures that could cause long shutdowns are frequently eliminated because the proper corrective action would be taken before real damage is done.

5.10 Reliability

Section 5.7.7 of this report discussed the number and types of failures that occurred during the testing. It also pointed out that the majority of failures were due to cell overvoltage caused by cell cracks and electrolyte maldistribution. Only a few failures were caused by mechanical equipment. Before the problem of system reliability is considered it will be necessary to eliminate the frequent shutdowns caused by electrolyte maldistribution. When that problem is solved, and proper steady state operation can be obtained, reliability of other components should be considered. Quality assurance of components and high reliability electronic parts should also be included. Reliability of the mechanical components can be improved by using quality hardware that has been proven to be compatible with KOH in long term operation. Plumbing assemblies should be fabricated to eliminate potential leak points by using welded tube joints, etc.

Reliability of cell and module designs can be improved considerably. Some of these problems are discussed in sections 5.7.7.1 and 5.7.7.2. Improvements include: better assembly techniques of modules to eliminate soldering requirement, greater strength in spacer plate, better flow characteristics through turn-around plate, new location for water feed if intermittent circulation is a requirement, improve temperature control, eliminate requirement for internal heaters in cells, improve o-ring grooves to meet standards, eliminate problem of stray electrolysis in cells, improve design of cells to be more uniform in thickness, and eliminate the requirement for shims between cells to provide electrode matrix compression. Accomplishing the aforementioned changes or improvements would result in a reliable system suitable for consideration on future space vehicles.

5.11 Hazards and Safety Concerns

Careful review of SVFU design and operation during the 182-day test has not revealed any hazardous or unsafe conditions. One area that caused some concern was the addition of solenoid valves in the water discharge line from the modules. By adding these valves, which were normally closed except when the circulation pump is operating, the water cavity became isolated from the differential pressure switch. The purpose of the switch was to protect the system from excessive water pressure. This was a concern because if the water pressure became excessive it would have been possible to destroy one or more cell matrices, allow flooding of the hydrogen cavity, and allow excessive water carryover through the hydrogen gas discharge line. Unless an operator observed this carryover or the water accumulator went dry, the system would continue to operate. Additional protection is required if solenoid valves are to be used at both the inlet and outlet water lines of the modules. Relocating the sensing location of the differential pressure switch could solve the problem.

Other hazards or safety concerns that were reviewed pertinent to the SVFU include: environmental extremes exceeding personnel and equipment tolerances, energy sources, electrical overload, electrical shock, inadvertent actuations, current limiting and other safety decives, fire suppression, toxicity, biological growth, caution/warning devices, time constraints, emergency procedures and power source failures. All of these items were adequately covered by the final configuration of the system except possibly the use of flammable materials within the unit and the toxicity of some non-metallic parts. These investigations would be made if the unit were to be used in a closed environment. Building the unit to meet these conditions was not part of the existing test program. One other characteristic of the unit was lack of integral containment for any leaking KOH. The exposed design allowed all leaking KOH to fall to the floor without damaging other components. The leaks were caught in a drip pan provided for the purpose. This concept would be inadequate for a reduced gravity environment.

5.12 Interface Requirements for Spacecraft Applications

The static feed water electrolysis system is a definite candidate for on-board spacecraft oxygen generation. Its inherent advantages are based on the potential simplicity of the system which results directly in improved reliability and decreased development costs. Also, it has available growth potential. Its use of an alkaline electrolyte minimizes construction material corrosion problems. Incorporating its electrolyte into a porous matrix results in low power requirements and provides a simple mechanism for separating product gases. Its mode of static water feed is self-regulating, simple, minimizes controls, prevents cell electrodes from becoming contaminated with unremoved water impurities and avoids high capacity liquid-gas separators. All of these characteristics make the static feed concept of water electrolysis desirable for spacecraft applications. However, based on the testing experience gained in conducting the 26-week test program, certain interface requirements and design changes presented themselves as desirable should the SVFU be selected for spacecraft applications. None of the suggested changes should be considered negative comments as it is recognized that the system as presently configured was not designed for spacecraft application but was designed for special terrestrial testing. The suggested changes briefly stated are as follows:

- Eliminate the requirement for multiple power sources. Presently the unit requires two power sources. It is suggested that the complete system be modified to require only one power source compatible with that available in the spacecraft. Along with this change, it is suggested that the system retain its low suscepitbility to power supply ripple and rigid regulation.

- One of the major changes to the system will be to make it operable in a null gravity environment. Gravity type gas-liquid separators, vent traps, and carryover traps will have to be eliminated or replaced by null gravity types. Proper design and use of a more mature cell and module design may automatically eliminate some of the gravity dependent components.

- Some of the hardware used in the construction of the unit is not space compatible, thus, replacing non-compatible equipment with compatible equipment and flight qualifying the system may change its performance characteristics considerably.

- The system should be modified to be compatible with the on-board checkout system of the space vehicle. This was partially done in the test program in that parameters were recorded, monitored and displayed remotely from the unit. Additional channels of data, relative to the status of electronic circuits, should be brought out of the system for remote monitoring and display. Mass balance data should also be included in the monitoring and checkout system.

- Packaging density of the SVFU, as used in this test program, was extremely low. This had the advantage of easy maintenance. Spacecraft applications cannot afford the luxury of large volume, therefore better packaging to decrease the volume is required. Easy access for maintenance should be retained as long down times of the system could be extremely detrimental to the space crew and mission.

- Nitrogen was used as a pressurization gas for the regulators and the water feed accumulator. The consumption rate was low when the system was operating properly but increased to undesirable levels when a failure of the regulator disphragms occurred. A redesign of the system plumbing could eliminate the requirement for N_2. Oxygen could be used in its place as was done during the 100-hour acceptance testing at LSI. Care should be exercised to ensure that hazardous conditions do not get into the system as was experiences prior to the 90-day manned test.

- Leakage was a major problem during testing and could be even more severe in a null gravity environment of a spacecraft. If leaks occur, contamination problems will exist for the crew and the contaminant control system. Therefore, a method of KOH containment is recommended to: 1) minimize the amount of KOH solution that can leak out should a fitting, line, cell, etc., break and 2) provide an internal self-contained blower/filter system and absorbent pads to collect the leakage before it can escape the envelope of the electrolysis unit.

- Plumbing changes should be made to minimize the quantity of plumbing, valves, fittings, etc., in the system to reduce the number of potential leak points. Some segments of the plumbing should be made into assemblies with welded joints. Plastic tubing should be eliminated wherever possible due to its susceptibility to hot flow and leakage as was experienced during the 100-hour acceptance testing at LSI and to a lesser extent during the 182-day test.

- Redesign the system to incorporate automatic startup, shutdown and pressure control during both startup and shutdown. Improvements should also be made for improved pressure differential control and easier methods of increasing and decreasing system pressures. These will be important changes, but necessary if the system is to be used in space by personnel less experienced than the system designers. Also, the system can be more easily integrated with the on-board checkout system if automatic operations are incorporated. Observance of system performance by space crews will be lessened by automatic controls.

- A new more efficient current control unit will be required for spacecraft applications. Efficiences of less than 80% will be considered undesirable for space. Switching regulators hold promise for use in a redesign of the system.

- Electrolyte temperature control was a problem in the 182-day test. Therefore, redesign for space applications should consider very carefully the entire thermal control problem of the SVFU. Plumbing lengths should be kept short, heated plumbing should be well insulated, and heating requirements eliminated completely if at all possible.

- Stray electrolysis hindered some operations during testing. Redesign should eliminate the sources and causes of stray electrolysis. This problem is closely related to cell and module designs. It is assumed that major improvements in both cell and module designs will be made. Thus, this problem of the system may be simultaneously eliminated.

- Before the concept of the SVFU, as tested, can be used in space applications major changes will be required to the cells and modules. Major problems of the cells that will have to be solved prior to its use in space include: elimination of leaks between cells by fabricating flatter, more uniform cells and o-ring grooves such that o-rings seal better, less compression is required and shims are eliminated; improving water feed geometry to eliminate electrolyte distribution problems and to permit long-term operation; reducing feed matrix restrictions to allow more efficient vapor transfer, back diffusion of KOH, and easier purging of gases trapped in the water cavities. Cell heaters should also be eliminated by a redesign to reduce thermal stressing of cell construction material. A more desirable cell material should be investigated as a possible replacement for polysulfone should additional testing indicate that type of change desirable. Whether or not the concept of a unitized cell should be eliminated would depend on improvements made within the cells, modules and system.

- Module changes deemed desireable for space applications include relocating water feed to allow intermittent circulation of electrolyte without the problem of electrolyte washout in the end cells and without interference from trapped gas collecting in the cell manifolds. Additional testing with these type of cells will be required to verify that intermittent water feed is an acceptable concept. Pressure drop through the module during circulations (if required) should be reduced to allow more efficient flow for gas purging. A major problem during testing was the considerable amount of soldering and unsoldering that had to be done to assemble and disassemble a module. A better method of electrode connections and cell heater (if required) connections is required. Down time of a module would have been reduced considerably if an easier method of assembly and disassembly existed. It is estimated that 50 to 70% of assembly and disassembly time was spent in soldering and unsoldering connections.

6.0 MONITORING AND SAFE-CONTROL SYSTEM

The monitoring and safe-control system was setup to monitor the performance of both water electrolysis systems, identify when monitored parameters went out-of-tolerance and shutdown part or all of the SVFU to prevent system damage due to internal malfunctions. The data system equipment was assembled, fabricated, and integrated under the sponsorship of the McDonnell Douglas Astronautics Company inhouse capital funding. Computer programming of the CDC 8090 computer and checkout of computer peripheral equipment was done under the sponsorship of Independent Research and Development program funding. The CDC 8090 computer and associated CDC 1612 line printer were provided to the program as Government Furnished Equipment (GFE).

6.1 System Description

A data acquistion and performance monitoring system was used to monitor the system operation and display pertinent data on the two electrolysis units. The system consisted of a signal conditioning console, a Dymec data acquisition unit with a Kennedy magnetic tape recorder, an interface unit, a CDC 8090 computer and a CDC 1612 on-line printer. Approximately 200 channels of data from the two electrolysis units were monitored. Data was recorded on magnetic tape at one-minute intervals. The raw data into the data acquisition system was recorded by the system and simultaneously delivered through the computer interface unit to the computer for comparison of each data signal with a preset value in memory. If a parameter was out of tolerance, a signal was returned to the interface unit which sent a control signal back to the malperforming portion of the SVFU electrolysis system. In this manner it was possible to shut off a single module of the SVFU or the entire electrolysis unit.

Whenever a failure or out-of-tolerance condition occurred the on-line printer printed a shutdown word indicating which part of the system was out of tolerance and printed out test day, clock time, complete data dump of all channels of data, and placed an asterisk (*) adjacent to the out-of-tolerance channel. Data was printed at 1-minute, 10-minute or 1-hour intervals as selected by the operator. At midnight, the monitoring system printed a summary of the previous day's data. Each channel displayed an average value as well as the high and low value experienced by that channel during the preceding 24-hour period. Off-line data reduction on a SDS 930 computer was also available if problems were encountered that required additional diagnostic data. This was done a number of times during the testing.

Data monitored and indicated by the acquisition system included cell and module voltages, module current, system current and voltage, system pressures, temperatures and liquid flow, on/off status, changes in operating modes, calibration data and ambient temperature. All parameters were indicated in engineering units except pressure data which was given in millivolts.

6.2 Sample Data

Figure 6-1 shows a typical printout from the on-line printer for 1100 on test day 029. The figure shows the date-time group on the top line and that this is a normal data dump occurring once each hour. If a malfunction had occurred, another line would appear above the date-time group indicating the general point of failure. The shutdown word was a code to indicate which module shut down. The body of the data would give more specific information as to why. For example, if cell 15 of module position 2 had too high a cell voltage, an asterisk would appear to the right of the channel for cell 15 module 2 indicating malfunction.

All data channels of the monitoring system are presented including calibration channels and spare channels. The left column identifies the first channel of data in that line. Each line contains five channels of data.

```
 DAY 029   TIME 11H 00M 00S HOURLY DATA DUMP
000     AM1C01V +001.577    AM1C02V +001.579    AM1C03V +001.585    AM1C04V +001.591    AM1C05V +001.581
005     AM1C06V +001.581    AM1C07V +001.569    AM1C08V +001.553    AM1C09V +001.565    AM1C10V +001.567
010     AM1C11V +001.571    AM1C12V +001.579    AM1C13V +001.596    AM1C14V +001.573    AM1C15V +001.622
015     AM2C01V +001.569    AM2C02V +001.591    AM2C03V +001.571    AM2C04V +001.573    AM2C05V +001.573
020     AM2C06V +001.602    AM2C07V +001.557    AM2C08V +001.579    AM2C09V +001.575    AM2C10V +001.596
025     AM2C11V +001.569    AM2C12V +001.569    AM2C13V +001.606    AM2C14V +001.589    AM2C15V +001.591
030     AM3C01V +001.575    AM3C02V +001.600    AM3C03V +001.579    AM3C04V +001.585    AM3C05V +001.571
035     AM3C06V +001.585    AM3C07V +001.577    AM3C08V +001.579    AM3C09V +001.577    AM3C10V +001.557
040     AM3C11V +001.573    AM3C12V +001.569    AM3C13V +001.612    AM3C14V +001.547    AM3C15V +001.535
045     ASYT01P +000.604    ASYT02P +000.612    ASYT03P +000.002    ASYT04P +000.026    ASYT05P +000.399
050     ASYT06P +000.481    ASYT07P +000.733    ASYT08P +000.469    ASYT09P +000.012    ASYT10P +000.702
055     ASYT11P +000.958    ASYT12P +000.694    LSYT01P +001.991    LSYT02P +002.041    LSYT03P +002.747
060     ASYT01T +012.031    ASYT02T +008.563    ASYT03T +008.675    ASYT04T +008.750    ASYT05T +023.938
065     ASYT06T +024.063    ASYT07T +021.031    ASYT08T +020.313    ASYT09T +023.031    ASYT10T +025.125
070     ASYT11T +027.406    ASYT12T +027.406    ASYT13T +034.844    ASYT14T +008.563    CALTEMP +022.156
075     AM1T--I +011.414    AM2T--I +011.414    AM3T--I +011.477    AM3TC3T +076.750    AM3TC4T +065.000
080     AM1TC1T +080.500    AM1TC2T +070.875    AM1TC3T +076.813    AM1TC4T +077.875    AM2TC1T +080.688
085     AM2TC2T +060.813    AM2TC3T +076.188    AM2TC4T +043.906    AM3TC1T +084.813    AM3TC2T +068.750
090     CALPRES +000.004    SPARE   -000.358    AM1T--V +023.688    AM2T--V +023.719    AM3T--V +023.641
095     ASYT--V +032.063    ASYT--I +037.063    ASYT01F -000.000    ASYT02F +001.869    ASYT03F +001.627
100     LM1A01V +001.787    LM1A02V +001.844    LM1A03V +001.772    LM1A04V +001.797    LM1A05V +001.774
105     LM1A06V +001.797    LM1A07V +001.793    LM1A08V +001.795    LM1AT-V +014.375    LM1B01V +001.803
110     LM1B02V +001.801    LM1B03V +001.781    LM1B04V +001.764    LM1B05V +001.760    LM1B06V +001.791
115     LM1B07V +001.774    LM1B08V +001.843    LM1BT-V +014.329    LM2A01V +001.801    LM2A02V +001.803
120     LM2A03V +001.807    LM2A04V +001.778    LM2A05V +001.793    LM2A06V +001.768    LM2A07V +001.797
125     LM2A08V +001.787    LM2AT-V +014.344    LM2B01V +001.837    LM2B02V +001.809    LM2B03V +001.797
130     LM2B04V +001.776    LM2B05V +001.762    LM2B06V +001.762    LM2B07V +001.772    LM2B08V +001.770
135     LM2BT-V +014.281    LM3A01V +001.817    LM3A02V +001.827    LM3A03V +001.805    LM3A04V +001.799
140     LM3A05V +001.611    LM3A06V +001.754    LM3A07V +001.752    LM3A08V +001.756    LM3AT-V +014.329
145     LM3B01V +001.621    LM3B02V +001.791    LM3B03V +001.781    LM3B04V +001.756    LM3B05V +001.770
150     LM3B06V +001.743    LM3B07V +001.781    LM3B08V +001.776    LM3BT-V +014.227    LM4A01V +001.620
155     LM4A02V +001.610    LM4A03V +001.608    LM4A04V +001.598    LM4A05V +001.606    LM4A06V +001.589
160     LM4A07V +001.604    LM4A08V +001.598    LM4AT-V +012.837    LM4B01V +001.678    LM4B02V +001.662
165     LM4B03V +001.666    LM4B04V +001.641    LM4B05V +001.647    LM4B06V +001.637    LM4B07V +001.670
170     LM4B08V +001.680    LM4BT-V +013.274    CAL-01  -000.000    CAL-02  -006.270    ASYLOGP +005.184
175     LSYT--I +000.014    LM1AT-I -012.102    LM1BT-I +012.414    LM2AT-I +012.477    LM2BT-I +012.414
180     LM3AT-I +012.281    LM3BT-I +012.555    LM4AT-I +005.071    LM4BT-I +006.958    SPARE03 -002.395
185     LSYT01T +028.422    LSYT02T +027.875    LSYT03T +026.500    LSYT04T +027.344    LSYT05T +032.250
190     LSYT06T +024.860    LSYT07T +030.204    ASTATUS +031.906    SPARE   -001.533    SPARE   +001.672
195     SPARE   +000.208    SPARE   +000.006    LMODE   +003.188    ASST--V +005.243*   LSTATUS +004.098
```

FIGURE 6-1. SAMPLE DATA DUMP

Each channel printout includes a seven place alpha-numeric printout identification code and a six digit printout of the value in engineering units, for example, AM1C08V + 001.583 means Allis-Chalmers (SVFU) module 1, cell 8 voltage is 1.583 volts. Another, ASYT--I designates Allis-Chalmers system current total. The first letter indicates the system A = Allis-Chalmers (SVFU) or L = Lockheed (CEU). The last letter indicates the characteristics, I = current, V = voltage, P = pressure (This was a millivolt unit and required a separate calibration curve to obtain engineering units), F = flow and T = temperature.

6.3 Performance Results

Overall the monitoring and safe-control system worked very well throughout the 182-day testing period. A few problems were encountered but nothing major and only a limited amount of actual data was lost because of failure of this system. Only once was it necessary for the SVFU to be shutdown or remain nonoperational due to data system failure. On 24 October 1971 an electrical storm in the area caused the building lighting to flicker sufficiently long to cause the Dymec and computer to shutdown. The recording system was nonoperational from 1310 until 1810 at which time the equipment was restarted. The electrolysis units were not affected by the monitoring system shutdown and continued to operate successfully during the period. Unfortunately, no data was collected for that 5-hour period. The second problem occurred at 2246 hours on 2 November 1971. In this case the printer stopped printing for no evident reason. The printer was reactivated at 0740 hours on 3 November. Data was continuously recorded on the Dymec system. Representatives of CDC investigated the failure and could find no cause for the shutdown and suggested no corrective action until the problem was repeated. A problem was encountered on November 19 that caused a momentary (5 seconds) shutdown of the SVFU. This problem occurred during a Dymec tape change when the technician did not follow the prescribed procedures properly. The technician rewound the magnetic tape during the period that the computer was reading data. This automatically stopped data to the computer and 2 minutes later the computer indicated "2-minute delay experienced" and shut the SVFU down. The procedure for tape changing was modified to prevent a reoccurrance of this cause of shutdown.

Limit values on all the CEU monitored channels were not orginally on the limit tapes, these were added to assist the LMSC resident engineer in failure diagnosis. All limit values were reviewed and approved by the Lockheed program manager. The purpose of the limit values was to indicate when and if a monitored channel on the CEU went out of tolerance. The computer was programmed to not shut the CEU down but would print out the time and dump data to show what channel was out of tolerance and how far out of tolerance.

On 3 December a problem occurred at 0802 during data recordings by the system operators. None of the data channels were out of tolerance. Investigation by computer personnel identified that the computer had modified internal instructions by dropping one bit from memory. The program and limits tape were reloaded and the system appeared to operate correctly. A review of the computer history revealed that one of five similar Saturn computers had done a similar thing once in 6 years and no explanation was ever found.

The next problem occurred on 19 December at 0607. The computer tried to shutoff module 2 due to overvoltage in cell 9 but the signal was never received by the module electronics. An attempt was made to duplicate the shutdown signal. The signal was received by the module and proper logic signals would actuate to shutdown the module. The only corrective action taken was to disconnect and reconnect the computer signal input plug to the SVFU.

A third computer malfunction occurred at 1204 on 28 December when the computer self-test was not recognized. This means that the computer and the interface unit were not communicating properly. Checking equipment did not produce any cause for the anomoly. The computer program was reloaded and seemed to be working normally.

Another problem occurred with the computer but did not cause a system shutdown. On 4 January the computer over-temperature light flashed on a few times. All the filters were removed and cleaned, the problem disappeared. Filters were cleaned monthly thereafter. On 5 January the computer and typewriter were adjusted by the manufacturers representatives. A new bushing on the drive drum was required, as well as a general cleaning. A number of light bulbs were replaced on the computer console to enhance malfunction diagnosis. Two integrated circuit cards were also replaced.

During January the Control Data Corporation personnel were required to repair and adjust the printer. Unfortunately the repairs were not 100% successful. The printer operated with more success in the sense that it did not arbitrarily shutdown but it did not print as clearly and uniformly as before. According to CDC personnel a new clutch and brake assembly was required. Normal life of this assembly is 2000 hours or 1 year of 1-shift operation. This test had exceeded this time period after 4 months because of 3-shift operations. A new assembly was to be installed as soon as it was available and/or a convenient interval of time occurred. However, this repair was not performed in the test period. An integrated circuit card was replaced in the printer logic that seemed to have eliminated stray shutdowns of the printer.

The data system was shutdown for a few days when both electrolysis units were off for corrective maintenance. During that off period a few checkout tests were performed on the Dymec and a number of burned out light bubls were replaced.

On 3 April it was noticed that the Kennedy tape recorder panel lights were out. The system was restarted and seemed to be all right. It was suspected that there was a momentary power loss. Other components in the data system were not affected. The electrolysis systems were not shutdown. Data between 0801 and 0823 was lost.

On 4 April the Dymec, Kennedy tape recorder, and interface box power cord disconnected. To prevent shutdown of the SVFU the shutdown signal cable to the SVFU was disconnected. Next the data system was repowered and checked out. There was no evidence of any other problem and the systems seemed to be working properly. The SVFU shutdown signal cable was reconnected. Fortunately, personnel observed the shutdown of the data system in time to prevent inadvertent shutdown of the SVFU by the "2-minute limit expired" signal.

The next failure occurred at approximately 1532 on 6 April. Again the Dymec shutdown. The problem was traced to the Dymec magnetic tape coupler. A resistor in the logic circuit failed due to an underrated component. The 5 resistors and 2 transistors were replaced and the system put back in operation at 0900 on 7 April. The SVFU was automatically shutdown with this failure.

The final problem occurred on 14 April which caused a shutdown of the SVFU. The printout occurring at 2045 indicated two consecutive synchronization errors. Troubleshooting determined that the Kennedy tape recorder was not advancing the tape. The power to the recorder was cycled on and off but this did not help. All the cards in the tape coupler box were wiggled and after one scan the tape started to advance. The SVFU was restarted and the data system operated successfully until 17 April. At this time the data system engineer determined that one transistor in the magnetic tape coupler and one transistor in the interface box were not performing satisfactorily and were extremely sensitive to heat. These items were replaced and the system monitored closely that day. The system operated satisfactorily until the end of the test.

The data system failures can be grouped into three categories of four failures each: a) stray noise, b) human error and c) equipment wearout. The stray noise was traced to stray electronic signals that entered into the system from other laboratory equipment and from a portable welding unit. The human error failures were caused by improper magnetic tape changing procedures by the technicians, two interface electrical plugs working loose (these should have been checked weekly) and dirty filters on the computer (these should have been cleaned monthly). Equipment wearout of data system components necessitated replacing two circuit boards in the computer, one circuit board in the on-line printer and two circuit boards in the Dymec data acquisition unit.

After operating the data system for 26-weeks certain shortcomings became evident. It would be desirable to eliminate these shortcomings for future testing and at the same time upgrade the data system for greater flexibility and versatility. Some of the major changes that should be made include:

- Use of additional bilevel channels with on-line revision and implementation
- Use of a CRT for input/output for data revisions (i.e., update display off line, then transmit to computer).
- Direct analysis of trends by computer from recorded data.
- Capability to enter additional data to the computer for analysis. For example, mass balance data, parasitic power data and nitrogen consumption data.
- Ability to create new limits tape from limits in memory. This would simplify computer loading and changing or adding limits. CEU limits had to be hand typed each time the limits were loaded.
- Ability for real time display of any one channel without interrupting normal data taking operations. Possibly use a CRT.

- Automatic restart of computer in event of power failure.
- Ability to revise limits using engineering values rather than the raw data presently required.
- Ability to enter zeros and offsets on pressures and to display pressures in engineering units.
- Ability to set negative limits and ability to set limits on:
  - a) negative number less negative = out of tolerance
  - b) negative number more negative = out of tolerance
  - c) positive number less positive = out of tolerance
  - d) positive number more positive = out of tolerance (This last item exists now.)

7.0 CONCLUSIONS AND RECOMMENDATIONS

The primary objectives of the 182-day test program were met. Sufficient data was collected and analyzed to ascertain the design maturity of each system and to assess the types of programs required in future development efforts. It was also concluded that water electrolysis technology at the system level was not as advanced as previously surmised. Both system concepts require extensive development and testing before they are truly adaptable to spacecraft installation and zero-g operation.

The circulating electrolyte electrolysis unit operated as intended and successfully met all planned test objectives. No cell or module failures occurred and the 0.85 ratio of successfully completed to scheduled module hours would have been even higher if multi-shift operation and ample spares inventories had been provided. The time attributed to actual labor (excluding fault diagnosis and troubleshooting) for repairs of the CEU was estimated at five percent of the total down time.

The CEU energy requirements per kilogram of oxygen produced showed an increase of approximately 4.5% during the 6-month test program. Most of this increase was attributed to the experimental anodes in module 1 as the specific energy increase over the test period for modules 2, 3 and 4 was only about 2%. The 4.54 kg/day (10 lb/day) oxygen generation rate required about a 5% higher specific energy than the 3.63 kg/day (8 lb/day) rate. The 4.54 kg/day (10 lb/day) rate did not accelerate the long-term specific energy requirement increase. Orbital simulation using a 54-minute module-on period and a 38-minute off period resulted in a 5% reduction in specific energy requirements. Current controller efficiency has been identified as an area requiring improvement. An additional parasitic power penalty may be encountered by the CEU design if a compressor is required for pressurization of product gas.

Mass balance data for the CEU indicated a current efficiency of less than 100%. This was the result of shunt currents flowing from cell to cell through the circulating electrolyte. The current efficiency did not change with operating time and appeared to be higher at the higher production rates.

Control logic used in the CEU is highly developed and allowed completely hands-off operation, automatic startup and shutdown, and automatic safety shutdown. Most of the electronic difficulties which were experienced in the test program most likely would have been eliminated by flight item design and assembly with an associated rigorous quality assurance program. Additional work needs to be done to eliminate the susceptibility of the design to circuit noise and power supply ripple and regulation. A more flexible system may result if the safety circuitry were designed to shut off only the affected malperforming portion of the unit rather than the entire system.

The quantity of purge nitrogen used by the unit following an automatic shutdown would be excessive for spacecraft use. The volume of gas required could be significantly reduced if, after an initial purge, the nitrogen was recycled through the CEU.

It is recommended that the limitations on coolant pressure to the heat exchanger be eliminated from future designs.

The static vapor feed unit designed and tested under this program had eliminated many of the shortcomings of the peripheral system equipment and design that were inherent in the original A-C design. It was concluded from the literature review conducted that the total system as designed for the 90-day manned test at MDAC was, by design, unable to operate in the mode specified by the manufacturer.

Cell tests conducted by LSI showed that the cells tested were well within operating capacities over the current range investigated. Absolute levels of iR drop and terminal voltage and cell voltage at high current densities were found to be lower in the 1970 design cells than in the 1968 design cells. LSI tests showed that the 1970 cells were more affected by H_2 to H_2O Δp than the 1968 cells. From cell disassembly information it was concluded that major repairs at the cell level are impractical.

The static vapor feed electrolysis modules were successfully tested for 48 continuous hours by the module manufacturer (A-C) and for 100 continuous hours by LSI. Both tests used continuous circulation of electrolyte. No major problems were encountered at either test facility or during a 100 hour system checkout test at MDAC employing water feed to the liquid gas separator and circulation at 30-minute intervals. Significant problems were encountered, however, during the 80 hour checkout test and the 182-day test, both employing water feed to the modules and longer periods between circulations. It is concluded that the acceptance tests did not provide an adequate preview of the actual 182-day test performance due to the difference in operating conditions imposed.

Cell overvoltage caused approximately 80% of the SVFU module shutdowns. It is concluded that these shutdowns were caused by maldistribution of electrolyte within the cell matrices, electrodes, cavities and circulating loop of the system. Leaking check valves and electrolyte washout due to density gradients caused 47% of all SVFU failures.

The SVFU module energy requirements per kilogram of oxygen produced were essentially constant over the test period for nominal current/pressure operation. Insufficient operation at below or above nominal current/pressure operation was conducted to draw meaningful conclusions at these conditions.

More efficient thermal packaging would significantly reduce the total power required by the SVFU. Trade-off studies should be conducted to quantify power penalties for operation without cell heaters in an attempt to eliminate module heaters altogether. The portion of the total power input dissipated in the current controller network should be reduced in later designs.

Mass balance data indicated that the 1970 design cells operated with shunt current losses when used under the conditions of the testing. The average current efficiency in the first 7 weeks of testing when the 1970 design modules were used was 93%. The 1968 design module currents were limited due to the low vapor transfer rates caused by the Teflon sheet restricting flow but operated at essentially 100% current efficiency.

Although the SVFU nitrogen consumption was quite low, it is thought that this interface could be eliminated entirely and additional improvements in product gas pressure control could be made in future designs.

The test program demonstrated that the basic materials used in the cells, modules and circulating loop of the SVFU (polysulfone, Teflon, CRES, and ethylene propylene elastomer) were compatible with the system fluids. However, the problem of stress cracks in the polysulfone cells should be investigated further to determine if this is an inherent defect or if unreasonable stresses were imposed by manufacture, thermal cycling, and/or draw bolt loading.

The SVFU tested under this test program had eliminated many of the shortcomings inherent in the original A-C system design. It, however, was still limited to the existing modules which exhibited high vapor feed restrictions, KOH back diffusion limitations, and electrolyte distribution problems under the operating conditions established for this test program. The immediate development goals of static vapor feed electrolysis should be improved cell and module design to eliminate present performance limitations, revision of thermal control technique to reduce parasitic power penalties, elimination of the requirement for the circulating electrolyte loop, and elimination of cell heaters and all possible metal components which can come into contact with electrolyte and cause stray electrolysis. A final goal should include incorporation of a control system providing for automatic startup, shutdown, pressure attainment and safety shutdowns.

It was concluded that the product gas contamination by both the CEU and SVFU was quite low. KOH carryover was in very small quantities; however, downstream components should be designed to be compatible with this carryover or a removal system should be incorporated. Cross-contamination of the product gasses, as well as contamination by other gasses used in the system, was very minute. Most contaminants detected approached the accuracy of the detection device with the procedure used. With the exception of the uncleaned solenoid valves inadvertently installed in the CEU, organic contamination of the product gasses was not detected.

The performance of the data system used in this test program was quite good, as approximately a quarter million data scans of 200 channels each were recorded with few malfunctions. Recommendations for additional data system capability for future tests of this nature include:

a) More flexibility in setting and revising program limits. Additional bi-level indicator channels.

b) Improved ability to perform routine mass balance and other computational tasks, such as trend analysis, on the computer.

c) Improved display and ability to monitor specific functions while continuing to gather normal data.

d) Ability to store hourly data for later recall and operation by computer would be beneficial.

Problem areas recommended for development applicable to either system in future test programs include:

1. Required o-g hardware.
2. Versatile, efficient current controller.
3. Improved safety shutdown trend analysis and fault isolation.
4. Development of KOH containment system.
5. Develop compact but maintainable package.
6. Cell/module testing in all orientations.
7. Elimination of plastic parts (where incompatible with space vehicles).
8. Solution to problem of electrically floating liquid loop.
9. Reduction in variety and type of input power required.

This program has provided a wealth of useful information pertinent to the evaluation of water electrolysis systems. Trends have been identified under the long-term testing and suggestions made for eliminating major problem areas. The plans and procedures developed for this program are partially applicable to testing of other subsystems. Other electrolysis concepts and more advanced design can also be tested economically and efficiently under the conditions established for this program. Comprehensive evaluations can be made because of testing under uniform conditions and against similar comparators. It is recommended that long-term testing by an impartial evaluator be continued as a basis for system performance evaluations of single or multiple system concepts and/or for combinations of integrated subsystems.

8.0 REFERENCES

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